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NAVAL POSTGRADUATE SCHOOL MONTEREY, CALIFORNIA



THESIS

AUTOMATIC SENSITIVITY ANALYSIS FOR AN ARMY MODERNIZATION OPTIMIZATION MODEL

By

John Peter Johnson

June 1995

Thesis Advisor:

Richard E. Rosenthal

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**AUTOMATIC SENSITIVITY ANALYSIS FOR AN ARMY
MODERNIZATION OPTIMIZATION MODEL**

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This is an extremely turbulent period for the post-cold-war Army. Even though the tempo of operations has increased dramatically worldwide, a peace dividend is demanded, consequently placing substantial constraints on the Army's capital budgeting process. In spite of this, the senior leadership is determined to maintain a first-rate force capable of meeting the challenges of the future.

Currently, the Office of the Deputy Chief of Staff for Operations and Plans (DCSOPS), United States Army, is reviewing a decision tool known as the Research, Development and Acquisition Alternative Analyzer (RDA³) to support the development of the Army Modernization Plan (AMP). RDA³ is a mixed integer optimization model formulated in the General Algebraic Modeling System (GAMS) by Donahue (1992). It prioritizes modernization actions and optimally allocates scarce research and development funds.

The goal of this thesis work is to enhance RDA³ to provide the user with a more robust decision tool capable of providing a complete analysis of the entire decision space. Specifically, this study focuses on the unfunded investment projects in the RDA³ solution, which are collectively called the *losers list*. The idea is to automatically provide explanatory information as to why each project on the losers list is unfunded. This study uses techniques developed by Chinneck (1993) for identifying infeasibilities in linear programming models. Chinneck's techniques are specialized for the RDA³ context and extended to integer programming. Additionally, the idea of controlling the amount of change from one model run to another, known as persistence, is applied to RDA³.

THESIS DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

A. BACKGROUND

This is an extremely turbulent period for the post-cold-war Army. Even though the tempo of operations has increased dramatically worldwide, a peace dividend is demanded, consequently placing substantial constraints on the Army's capital budgeting process. In spite of this, the senior leadership is determined to maintain a first-rate force capable of meeting the challenges of the future.

Currently, the Office of the Deputy Chief of Staff for Operations and Plans (DCSOPS), United States Army, is reviewing a decision tool known as the *Research, Development and Acquisition Alternative Analyzer (RDA³)* to support the development of the Army Modernization Plan (AMP). RDA³ is a mixed integer optimization model formulated in the General Algebraic Modeling System (GAMS) by Donahue (1992). It prioritizes modernization actions and optimally allocates scarce research and development funds.

B. OBJECTIVE AND SCOPE

The goal of this thesis work is to enhance RDA³ to provide the user with a more robust decision tool capable of providing a complete analysis of the entire decision space. Specifically, this study focuses on the unfunded investment projects in the RDA³ solution, which are collectively called the *losers list*. The idea is to automatically provide explanatory information as to why each project on the losers list is unfunded. This study uses techniques developed by Chinneck (1993) for identifying infeasibilities in linear programming models. Chinneck's techniques are specialized for the RDA³ context and

extended to integer programming. Additionally, the idea of controlling the amount of change from one model run to another, known as persistence, is applied to RDA³.

C. AUTOMATIC SENSITIVITY ANALYSIS FOR RDA³

Understandably, the losers list is a pivotal issue and demands scrutiny. The general scheme is to attempt to force the losers one at a time into the optimal solution, re-solve the model and measure the effects. Both feasible and infeasible solutions are produced in these attempts. If forcing a loser into the solution causes infeasibility, Chinneck's algorithms are applied. Whereas Chinneck's research was motivated by the need to find data errors causing unintentional infeasibilities, the motivation for this study is to identify all the causes of infeasibility deliberately introduced.

D. APPLYING PERSISTENCE TO RDA³

The degree to which a model maintains the previous solution from run to run is known as *persistence* (Brown, Dell, Farmer, 1995). As a capital budgeting model to be employed periodically by DCSOPS, RDA³ requires a persistence capability for general acceptance. As the prioritizer of the U.S. Army, DCSOPS is not amenable to canceling projects and starting others everytime the budget changes. This study applies the persistence methodology to maintain consistency of results while performing sensitivity analysis on the budget profile. It is applied to study the impact of a budget change, while encouraging the original projects to remain in the solution.

E. CONCLUSIONS

RDA³, by itself, is a useful decision tool. It rapidly assimilates data and provides an optimal mix of research projects and an optimal allocation of scarce research and development dollars. However, this may not be sufficient information to make a decision concerning billions of dollars. This study develops and implements a GAMS formulation,

Sensitivity Analysis for RDA³, that automatically investigates a great portion of the decision space. After running this program, the decision maker understands the tradeoffs involved with unfunded projects, and in some cases may determine that some losers could in fact be funded. Policy decisions, which include the mandatory funding of certain projects as well as the funding relationships, are thoroughly reviewed. For the baseline data in this study, most of the mandated projects gained credibility through this review, but there were a few that deserve further scrutiny. For those losers that are not funded due to conflicts in the funding relationships, a clear story is presented that articulates precisely what the conflicts are. In every case, the scope of the problem for each loser is dramatically reduced, thus allowing the decision maker to compare the merits of projects on a remarkably small scale.

Additionally, a manually directed sensitivity analysis of the budget is possible. *Sensitivity Analysis for RDA³*, provides a capability to accomplish this in a way that is consistent with the decision maker's priorities. The decision maker can maximize the achievement of his capital budgeting goals, minimize the change to the current set of research projects, or seek a balance between achievement and change.

F. RELEVANCE TO THE ARMY

The usefulness of this study is directly linked to RDA³'s adoption as a capital budgeting tool for the United States Army. If DCSOPS decides to use RDA³ in the development of the Army Modernization Plan, then the integration of *Sensitivity Analysis for RDA³* will substantially enhance the analysis. Otherwise, the Army should consider providing a similar automatic sensitivity analysis capability to whatever model is used. Further research and commitment to automating the analysis could potentially streamline the interactive process between decision makers and analysts, and accelerate the overall decision cycle.

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I. INTRODUCTION

A. HISTORY OF THE PROBLEM

In September 1992 the Naval Postgraduate School delivered a decision tool designed to provide the United States Army's Training and Doctrine Command (TRADOC) with a flexible and responsive means of prioritizing modernization actions and optimally allocating scarce research and development funds. (Donahue, 1993) Proposed modernization actions for the Army consist of a wide variety of investment projects, from weapon systems to communication equipment, all intended to meet forecasted requirements as determined by the senior leadership. The decision tool is called the Research, Development and Acquisition Alternative Analyzer (RDA³). RDA³ is a mixed integer optimization model formulated in the General Algebraic Modeling System (GAMS). It provides a decision maker or an analyst with an optimal mix of investments from the original shopping list of proposals. Subsequent sensitivity analysis must then be done by manually changing parameters within the model and re-solving the optimization.

Currently the RDA³ model is being reviewed for use by the Office of the Deputy Chief of Staff for Operations and Plans (DCSOPS), U.S. Army. As a co-sponsor for this study, DCSOPS has identified the need for some improvements to the model. This study addresses those needs and provides additional recommendations for improvement.

B. OBJECTIVE

The goal of this thesis work is to enhance the existing model to provide the user with a more robust decision tool capable of providing a complete analysis of the entire decision space. Specifically, this study focuses on the unfunded investment projects from the initial

RDA³ model results, which are collectively called the *losers list*. The idea is to automatically provide the maximum amount of explanatory information as to why each project on the losers list is unfunded. This automatic sensitivity analysis is done efficiently in terms of time to execute.

C. CURRENT ARMY BUDGET ENVIRONMENT

1. Situation

This is an extremely turbulent period for the post-cold-war Army. Even though the tempo of operations has increased dramatically worldwide, a peace dividend is demanded, consequently placing substantial constraints on the Army's capital budgeting process. In spite of this, the senior leadership is determined to maintain a first-rate force capable of meeting the challenges of the future. To accomplish this, an aggressive modernization program will be pursued as the drawdown continues. Figure 1 shows the declining defense budget allocation from 1989 to 1995. For FY 1995, the Army's overall budget, known as the Total Obligation Authority (TOA) was approximately \$61.2 billion. Of this, 18.6% or \$11.4 billion was allocated to research, development, and acquisition (RDA) funding. The forecasted amount for FY 1996 is a reduction to \$10 billion and the downward trend is expected to continue. The Army's wish list of modernization actions greatly exceeds these amounts, hence the need for a decision tool that can prioritize and perform trade-off analysis. (Schmidt, May 1995)

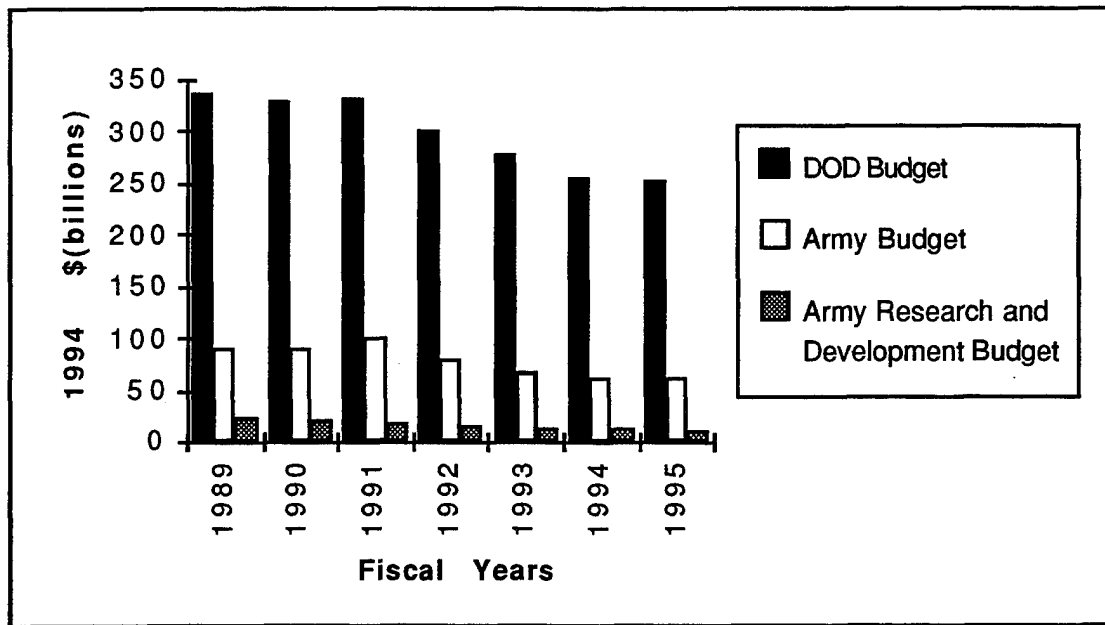


Figure 1. Budget Allocation FY89-FY95

2. Decision Making Demands

The reality of the Army's complex budgeting and procurement environment demands the presentation of options, as well as rationale for projects that go unfunded. Due to the decision maker's potential unfamiliarity with, or skepticism of mathematical programming models, the model must be able to anticipate sensible concerns. The decision makers want to know the impact of changes they may direct to the optimal mix of projects. Additionally, sponsors of unfunded proposals will expect justification. The objective for this study is to meet these demands and thus provide a useful decision tool.

II. DECISION SUPPORT MODELS FOR ARMY MODERNIZATION

This chapter provides the requisite background information on the Army's modernization program as well as the decision models used to prioritize projects and allocate funds. A detailed summary of RDA³ (Donahue, 1992) is included to facilitate the reader's understanding of the enhancements implemented by this study.

A. ARMY MODERNIZATION PLAN (AMP)

The Army develops its modernization plan after a careful evaluation of the strategic environment and the U.S. National Military Strategy. The current assessment of the strategic environment is that it is uncertain and unstable. A 300% increase in the number of operational deployments since 1989 is clear evidence of this assessment. The interested reader is directed to the 1995 United States Army Modernization Plan (Army, 1995) for a detailed accounting of this summary.

1. Force XXI

The current vision of the 21st century Army is known as *Force XXI*. It is essentially a redesigned force capable of meeting the challenges of the future. The concept of Force XXI envisions intellectual and physical change from the status quo. Intellectually, the digitization of the force and use of advance simulations are the key ingredients. Physically, the Army's downsizing, return from Europe and conversion into a power projection Army represent significant modifications in the shape of the Army. The power projection Army, based in CONUS will be characterized by a broader range of missions, severely constrained resources, 21st century technology, and a shorter planning horizon for action (Army, 1994). The AMP is a critical element in transitioning today's Army to Force XXI. (Army, 1995)

a. Joint Operations Doctrine

Force XXI is derived from joint precepts and doctrine and therefore, supports the top five Future Joint Warfighting Capabilities, shown below and discussed in Volume Four (Future Capabilities) of the Joint Planning Document. The emphasis on joint and multi-national operations will continue to increase into the future.

- Near perfect real time knowledge of enemy and near real time dissemination
- Promptly engage regional forces in decisive combat on a global basis
- Employ capabilities suitable to actions at the lower end of the spectrum of military operations which allow achievement of military objectives with minimum casualties and collateral damage
- Control the use of space
- Counter weapons of mass destruction and future ballistic and cruise missiles to CONUS and deployed forces.

(Army, 1995)

b. Modernization Objectives

The Army modernization objectives which support the joint doctrine and are necessary to accomplish the National Military Strategy of *Flexible and Selective Engagement* are listed below (JCS, 1995):

- Project and sustain the force
- Protect the force
- Conduct precision strike
- Win the information war
- Dominate maneuver

The AMP provides information on the systems required to accomplish these objectives. Each objective is addressed by either enhancing current systems or introducing new technologies. The emphasis is capabilities, not systems. Therefore, the improvement and life extension of current systems is favored when possible (Army, 1994). The Army's systematic approach is intended to be evolutionary, although many revolutionary concepts will be synthesized into the process. (Army, 1995)

2. Decision Making Process

a. TRADOC's Role

TRADOC is the architect of the Army's future. As such, they are the author of the Long Range Army Material Requirements Plan (LRAMRP) which looks out to a fifteen year time horizon. (Donahue, 1992) TRADOC designed a process called the Concept Based Requirements System (CBRS) that determines the warfighting capabilities required by the Army (Schmidt, May 1995). Additionally, TRADOC develops the doctrine for how the Army trains and fights, and proposes recommendations to the leadership on how the force should be organized. The interested reader is directed to Donahue's work (Donahue, 1992) for a complete review of TRADOC's role in the modernization process.

b. Project Advocates

A project advocate is defined here as an individual or organization that has a vested interest in the successful adoption and funding of a certain project. Within the Army's acquisition process there exist several advocates for any given system. The original initiator of the project request is certainly an advocate and may be a TRADOC training center such as the Infantry School, or a specific Unified or Specified Commander in Chief (CINC) such as the CINC Atlantic Command. Once a project is initiated Program Executive Officers (PEOs) and Program Managers (PMs) are assigned responsibility for its development. They are also active advocates for projects under their purview.

c. DCSOPS' Role

DCSOPS is the prioritizer of the Army Staff and, as such, is the author of the AMP, as well as one of the primary authors of the Program Objective Memorandum (POM). The POM is the Army's recommendation of planned expenditures for the ensuing five year period to the Department of Defense. DCSOPS determines which projects to initiate as well as how to allocate funds to projects currently under development. To accomplish this, DCSOPS must synthesis information from project advocates and then properly prioritize projects to meet the present and future needs of the Army. The result is known as the Army Research , Development, and Acquisition Plan (RDA Plan). (Schmidt, May 1995) It provides a 15-year plan of funding streams for the technologies and materiel solutions selected to meet the modernization objectives. DCSOPS also provides input into the Extended Planning Period (EPP), which looks five more years beyond the POM. The allocation of funds becomes a major and ongoing process, dictated by the ever fluctuating budget. (Schmidt, Jan 1995)

3. Categorization of Projects

Investment projects, known as Management Decision Packages (MDEP), considered for procurement are assigned to Battlefield Operating Systems (BOS). The BOS is a construct which clearly partitions all aspects of Army activity on and off the battlefield into sixteen areas. The Army balances emphasis between the BOSs so that no area is neglected, and indicates priority to those BOSs which are critical to the Army's vision of force modernization.

a. Battlefield Operating Systems (BOS)

- Air Defense (AD)
- Ammunition (AMM)
- Aviation (AVN)
- Command and Control (C2)
- Combat Service Support (CSS)
- Fire Support (FS)
- Horizontal Technology Integration (HTI)

- Base Operations Support (IBOS)
 - Intelligence and Electronic Warfare (IEW)
 - Information System Management (ISM)
 - Science and Technology Base (ISTB)
 - Training (ITRG)
 - Testing (ITST)
 - Maneuver (MAN)
 - Mobility (MOB)
 - Nuclear, Chemical and Biological (NBC)
- (Schmidt, 1995)

b. Management Decision Packages (MDEPs)

The MDEP is a resource management tool designed to give visibility to certain projects (Schmidt, May 1995). MDEPs may encompass broad areas such as small arms weapons, or ammunition. Therefore, each MDEP classification usually includes a set of sub-projects. Donahue (1992) referred to these sub-projects as increments. *Projects* and *sub-projects* are the lexicon primarily used in this study for clarity. The relationship between MDEPs and increments is captured within the RDA³ model, and will be discussed later.

B. DECISION SUPPORT MODELS

DCSOPS currently uses one decision model to guide the prioritization and allocation of funding. This model, known as Value Added Analysis (VAA) (Loerch, 1992), effectively compares only high priority combat weapon systems. This type of system accounts for about 40 of the approximately 350 projects under consideration at any one time. Recognizing this shortfall, the Assistant DCSOPS for Force Modernization has tasked the Concepts Analysis Agency to integrate the RDA³ model with VAA in order to completely evaluate all projects under consideration. (Schmidt, 1995)

1. Value Added Analysis (VAA)

VAA is a family of models developed by the Concepts Analysis Agency to optimize acquisition strategies across system types and to support decision making necessary to build the Army budget (Loerch, 1992). A key model within VAA is the

Explicit Effectiveness Module, where the effectiveness of each competing system is measured. This module uses results from combat simulations to assign effectiveness values to the systems. This methodology is not considered appropriate for comparing systems that cannot be explicitly modeled in a simulation, e.g., command and control systems, intelligence acquisition systems, etc. The interested reader is referred to Loerch (1992) for an in depth review of VAA.

2. Research, Development and Acquisition Alternative Analyzer (RDA³)

As stated earlier, to facilitate the reader's understanding of the enhancements implemented in this study, more detail is now provided on RDA³'s development and structure. The following review is what is necessary to fully understand the scope of the present study, but is by no means exhaustive. The reader is directed to Donahue (1992) for a full discussion. RDA³ is a mixed integer optimization model formulated in GAMS. Specifically, it is a multi-objective weighted linear goal program with the following goals and inelastic constraints:

Goals

- Maximize the total warfighting value for each year
- Maintain mission area balance
- Minimize funding turbulence

Inelastic constraints

- Fund mandated projects
- Adhere to budget restrictions
- Adhere to maximum operation and support costs
- Fund MDEPs incrementally
- Adhere to minimum incremental funding levels
- Enforce existing funding relationships (logical constraints)

The major strength of RDA³ over VAA is its capability to compare all projects (MDEPs) under consideration regardless of their associated BOS category. This is due to the way the effectiveness measures for the projects are obtained. The *warfighting value* highlighted in the first goal is the measure of effectiveness assigned to each project. This effectiveness measure is currently obtained from an application of the Analytic Hierarchy Process (AHP), but could be easily replaced by another value assessment methodology. AHP solicits subjective views from subject matter experts through pairwise comparisons of all the projects under consideration and returns a ranking or prioritization scheme. Unfortunately, AHP is problematic because it has been shown to suffer from rank reversal (McQuail, 1993). This shortcoming is not the focus of this study.

The *mission areas* in the second goal of RDA³ are used by TRADOC for project analysis, and are easily mapped into the BOS construct used by DCSOPS. The third goal is introduced to prevent significant spikes in the funding profile of any project throughout the time horizon. This goal encourages the allocation of funds to a project in a given year to be at least a pre-determined fraction of the previous year's funding, given that it was funded the year prior. The mandated projects in the first inelastic constraint are those projects that must be either partially or fully funded. The remaining inelastic constraints are described in the next section.

a. General Goal Program Formulation

The generic formulation for a goal program is shown below in Equation 2.1. Each goal constraint has an associated elastic variable or variables that account(s) for the stretching of the goal. The objective function minimizes these elastic variables, hence minimizing the total deviations from the aspired goals. This is done while maintaining strict compliance of the inelastic constraints and variable bounds. The identification of infeasibilities within a goal program is discussed in Chapter IV.

$$\begin{array}{l} \text{Minimize } \sum \text{Deviation from the goals} \\ \text{subject to: } \text{goal constraints} \\ \text{inelastic constraints} \\ \text{variable bounds} \end{array}$$

Equation 2.1

b. RDA³ Formulation

The RDA³ formulation, extracted from Donahue (1992), is presented below. An annual minimum funding level constraint not present in the original formulation is also included. The indices, data, and variables are summarized in Tables 1-6. The goal weights and scaling factors are shown in Table 4. Familiarity with these parameters will assist the reader's understanding of the enhancements discussed later.

Set	Definition
i	Management decision packages (MDEPs) or projects
j	MDEP increments or sub-projects
k	Mission area that is the proponent for the sub-project
t	Fiscal years in the time horizon under consideration

Table 1. RDA³ Indices (from Donahue(1992))

Input Parameter	Definition
BUDGET _t	Warfighting budget allocation (\$1000) for fiscal year t
ASPIRE _{ijt}	Aspired level of funding (\$1000) for the jth increment of MDEP i in fiscal year t
TOTASPIRE _{ij}	Total aspired funding (\$1000) for the jth increment of MDEP i across the time horizon
MINLEVEL _j	minimum increment funding level for MDEP increment j across the time horizon if it is funded at all
MINLEVYR _{ij}	minimum annual funding level for the jth increment of MDEP i (not included in Donahue (1992) formulation)
OSCOST _{ij}	Operation and support costs (\$1000) for the jth increment of MDEP i
RAMP _{ij}	Ramp-up funding factor for the jth increment of MDEP i; specified as a fraction of the previous year's funding level aspired for current year
MANDATE _{ij}	Congressionally mandated increment j of MDEP i; equals 1 if the jth increment of MDEP i is mandated; equals 0 otherwise
SHAREDATA _{k,minimum}	Minimum level of funding (% of annual budget) for mission area k
SHAREDATA _{k,desired}	Desired level of funding (% of annual budget) for mission area k
SHAREDATA _{k,maximum}	Maximum level of funding (% of annual budget) for mission area k
MAXOSCOST	Maximum value for operation and support costs (\$1000) over the time horizon
WARVAL _{ij}	Composite priority weight factor (AHP warfighting value) for the jth increment of MDEP i

Table 2. Input Data (from Donahue (1992))

Derived scalar/parameter	Definition	Derivation
TOTOSCOST	Total operation and support costs (\$1000) for all MDEP increments across the time horizon	$\sum_{IJ} OSCOST_{IJ}$
MAXWARVAL _t	Maximum warfighting value in fiscal year t; equals the sum of the proportional composite priority weight factors in fiscal year t	$\frac{\sum_i \sum_j \frac{WARVAL_{ij}}{TOTASPIRE_{ij}}}{\sum_{i' \leq t} ASPIRE_{i'j'}}$

Table 3. Derived Data (from Donahue (1992))

Weights/Scaling Factors	Definition
WT1	Priority weight of warfighting goal
WT2	Priority weight of mission area balance goal
WT3	Priority weight of turbulence goal
WEIGHT1 _t	Discounted weight of warfighting goal in fiscal year t
WEIGHT2 _t	Discounted weight of mission area balance goal in fiscal year t
WEIGHT3 _t	Elastic penalties for mission area balance goal in fiscal year t
WEIGHT4 _t	Discounted weight of turbulence goal in fiscal year t

Table 4. Goal Weights and Scaling Factors (from Donahue (1992))

Decision Variable	Definition	Range
X _{ijt}	Fraction of aspired level of funding for the jth increment of MDEP i in fiscal year t	0 to 1
Z _{ij}	$\begin{cases} 1; & \text{if the } j\text{th increment of MDEP } i \text{ is funded} \\ 0; & \text{otherwise} \end{cases}$	0 or 1

Table 5. Decision Variables (from Donahue (1992))

Positive Variable	Definition	Range
NWARVAL _t	Negative deviation from aspired warfighting value in fiscal year t	0 to +∞
NBAL1 _{kt}	Negative deviation from desired level of funding for mission area k in fiscal year t	0 to +∞
NBAL2 _{kt}	Negative deviation from minimum level of funding for mission area k in fiscal year t	0 to +∞
PBAL1 _{kt}	Positive deviation from desired level of funding for mission area k in fiscal year t	0 to +∞
PBAL2 _{kt}	Positive deviation from maximum level of funding for mission area k in fiscal year t	0 to +∞
NTURB _{ijt}	Negative deviation from stable funding of the jth increment of MDEP i in fiscal year t	0 to +∞

Table 6. Deviation Variables (from Donahue (1992))

Objective function:

$$\begin{aligned}
\text{Deviation} = & \sum_t \text{WEIGHT } 1_t \cdot \text{NWARVAL}_t + \sum_k \sum_t \text{WEIGHT } 2_t \cdot \text{NBAL1}_{kt} \\
& + \sum_k \sum_t \text{WEIGHT } 3_t \cdot \text{NBAL2}_{kt} + \sum_k \sum_t \text{WEIGHT } 2_t \cdot \text{PBAL1}_{kt} \\
& + \sum_k \sum_t \text{WEIGHT } 3_t \cdot \text{PBAL2}_{kt} + \sum_i \sum_j \sum_t \frac{\text{WEIGHT } 4_t}{\text{SCALTURB}} \cdot \text{NTURB}_{ijt}
\end{aligned}$$

subject to:

$$\sum_i \sum_j \frac{\text{WARVAL}_{ij}}{\text{TOTASPIRE}_{ij}} \cdot \sum_{t \leq t} \text{ASPIRE}_{ijt} \cdot X_{ijt} + \text{NWARVAL}_t = \text{MAXWARVAL}_t; \quad \forall t$$

Achieve Desired Warfighting Value

$$\sum_{i \in k} \sum_{j \in k} X_{ijt} \cdot \frac{\text{ASPIRE}_{ijt}}{\text{BUDGET}_t} + \text{NBAL1}_{kt} + \text{NBAL2}_{kt} - \text{PBAL1}_{kt} - \text{PBAL2}_{kt} = \text{SHAREDATA}_{k, \text{desired}}; \quad \forall k, t$$

Maintain Mission Area Balance

$$\text{NBAL1}_{kt} \leq \text{SHAREDATA}_{k, \text{desired}} - \text{SHAREDATA}_{k, \text{minimum}}; \quad \forall k, t$$

Minimum Mission Area Funding Level

$$\text{PBAL1}_{kt} \leq \text{SHAREDATA}_{k, \text{maximum}} - \text{SHAREDATA}_{k, \text{desired}}; \quad \forall k, t$$

Maximum Mission Area Funding Level

$$X_{ijt} \geq RAMP_{ij} \cdot X_{ijt-1} - NTURB_{ijt}; \quad \forall i, j, t$$

Minimize Funding Turbulence

$$X_{ijt} \geq MANDATE_{ij}; \quad \forall i, j, t$$

Fund Mandated Projects

$$\sum_i \sum_j X_{ijt} \cdot \frac{ASPIRE_{ijt}}{BUDGET_t} \leq 1; \quad \forall t$$

Adhere to Budget Restrictions

$$\sum_i \sum_j OSCOST_{ij} \cdot \left(\sum_t X_{ijt} \cdot \frac{ASPIRE_{ijt}}{TOTASPIRE_{ij}} \right) \leq MAXOSCOST$$

Adhere to Maximum Operation and Support Costs

$$Z_{i,"01"} \geq Z_{ij}; \quad \forall i, j$$

Fund MDEPs Incrementally

$$\sum_t X_{ijt} \cdot \frac{ASPIRE_{ijt}}{TOTASPIRE_{ij}} \geq MINLEVEL_j \cdot Z_{ij}; \quad \forall i, j$$

Adhere to Minimum Incremental Funding Levels

$$X_{ijt} \geq MINLEVYR_{ij} \cdot Z_{ij}$$

Adhere to Minimum Annual Funding Levels (Not in Donahue (1992))

$$X_{ijt} \leq Z_{ij}; \quad \forall i, j, t$$

Link Discrete and Continuous Decision Variables

The last set of constraints, not included here, are what Donahue(1992) called the *logical constraints*. These constraints represent the funding relationships that exist between projects. They are described in detail in Chapter IV, where the term logical constraints is redefined to include all constraints that contain only binary variables. Once again, for a complete derivation and explanation of RDA³'s formulation the interested reader is directed to Donahue (1992).

III. IDENTIFYING INFEASIBILITIES IN LINEAR PROGRAMS

A. BACKGROUND

Significant advances in computers and software currently enable the routine formulation and solving of large, complex linear programs. However, as in all programming, mistakes are made while formulating large tasks or while updating previous work. In optimization models these mistakes can produce infeasibilities. Professor John Chinneck of Carleton University, Ottawa has established the methodological groundwork for analyzing this type of infeasibility in linear programming. Although others, including van Loon, proposed ways of dealing with infeasibilities, Chinneck was the first to develop a sound theoretical basis, coupled with actual implementation, that guaranteed the identification of a minimal set of inconsistent constraints. (Chinneck and Dravniek, 1991, Chinneck, 1993) This chapter is a brief summary of Chinneck's work.

B. IRREDUCIBLY INCONSISTENT SYSTEMS

Van Loon first coined the term *irreducible inconsistent system (IIS)*. (Chinneck and Dravniek, 1991) An IIS is an infeasible set of constraints to include variable bounds which would become feasible if any one member of the set is removed. Chinneck later refined the lexicon to include an *irreducibly inconstant set of functional constraints (IISF)*, which is a subset of an IIS. (Chinneck and Dravniek, 1991) The difference is the exclusion of variable bounds in the IISF. Figure 2 shows a set of constraints with the set {A,B,C} representing an IISF. The set of constraints shown in Figure 3 is not an IISF, however the sets {A,B,C} and {A,B,D} are both IISFs. One set alone only defines and explains a portion of the cause for infeasibility in the problem. Sometimes correcting (making

feasible) one IISF by removing one of its constraints will also correct other IISFs. This is the case when two or more IISFs contain common constraints. Removing either constraint A or B in Figure 3 corrects both of the IISFs present. The identification of a single IIS or IISF is considered critical to fix problems associated with mistakes in programming.

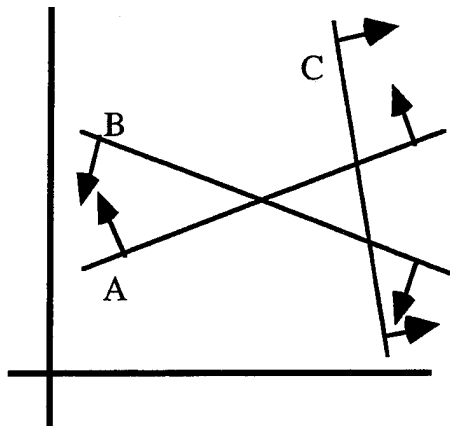


Figure 2. One IISF

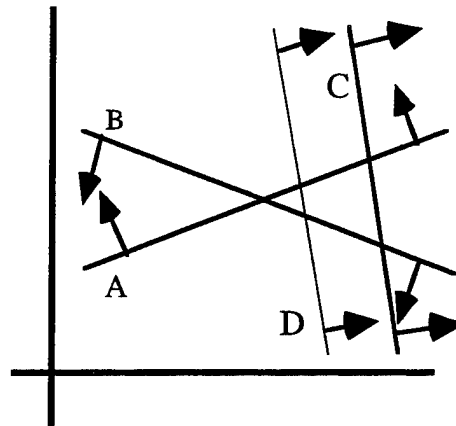


Figure 3. Two Overlapping IISFs

C. PINPOINTING INFEASIBLE CONSTRAINTS

In order to locate IISs and IISFs within an infeasible linear program Chinneck developed a series of algorithms called filters, as well as strategies to combine these filters for effective results. The four filters he developed are described below.

1. Deletion Filtering

Deletion filtering, by itself, is a brute force method of isolating a single IIS. The first step of the filter arbitrarily removes an existing constraint from the infeasible model. The model is then solved. If the model remains infeasible, the removed constraint is discarded (deleted). Otherwise, if the model becomes feasible, the removed constraint is replaced and another constraint is arbitrarily removed. This process is done iteratively until the removal of any constraint causes the model to become feasible. The remaining constraints together form an IIS. The IIS identified by the deletion process can change if

the constraints are considered in a different order. Constraints deleted may in fact contribute to infeasibility and constraints that are members of the isolated IIS may also contribute to other IISs. The IIS that is isolated by this filter, is the one that coincidentally does not have a member constraint tested until at least one constraint in every other existing IIS has been tested. The constraints of every other IIS will be eliminated in the process because the system remains infeasible until the last IIS is identified. Although some of the other filters are quicker at eliminating constraints that do not contribute to the infeasibility, the deletion filter must be used to confirm the identification of a single IIS.

2. Sensitivity Filtering

To find an initial basic feasible solution, most linear programming solvers employ the two phase method. In Phase I, artificial variables are added to each constraint or some other mechanism is used to allow infeasibility, and the objective function becomes the minimization of the sum of infeasibilities. For the new problem to be feasible, the objective value must equal zero. If so, a basic feasible solution is identified and the optimal value is obtained during Phase II (Bazaraa, Jarvis, Sherali, 1990). This filter uses the Phase I results for the infeasible case to determine if a constraint should be removed from the system. When Phase I confirms infeasibility in the original model, the non-basic variables with positive reduced costs will be associated with bounds and constraints that contribute to the infeasibility. They are said to be sensitive to the Phase I efforts. All other constraints with associated non-basic variables having a reduced cost of zero are eliminated from the system. The sensitivity filter isolates all non-overlapping IISs, and in practice finds the largest row size IIS of overlapped IISs.

3. Reciprocal Filtering

The foundation for the reciprocal filter is the theorem which states that given either a variable or functional constraint has finite upper and lower bounds, if it is infeasible at one bound then it cannot be infeasible at the other bound within the same IIS. This filter

can be used to eliminate unnecessary constraints by automatically identifying this condition while applying other filters.

4. Elastic Filtering

The elastic filter employs elastic programming techniques to identify IISs. The original model is converted to a pure elastic program by the addition of non-negative elastic variables to each functional constraint. These elastic variables allow each functional constraint to stretch beyond its bounds. The original objective function is replaced with the minimization of the sum of elastic variables. The form of the generic formulation conversion is displayed in Equation 3.1.

$$\begin{aligned}
 \text{Min or Max objective function} &\Rightarrow \text{Min} \sum_{ik} e_{jk} + \sum_j c_j x_j \\
 \text{st. } \sum_j a_j x_j \geq b_i &\Rightarrow \sum_j a_j x_j + e_i \geq b_i \\
 \sum_j a_j x_j \leq b_i &\Rightarrow \sum_j a_j x_j - e_i \leq b_i \\
 \sum_j a_j x_j = b_i &\Rightarrow \sum_j a_j x_j - e_{i1} + e_{i2} = b_i
 \end{aligned}$$

Equation 3.1 Conversion to an Elastic Formulation after (Chinneck, 1993)

When the system is solved the first time, at least one constraint in each IIS will stretch and an associated elastic variable will be positive. The stretched constraints are then forced to be feasible by removing their elastic variables from the formulation, and the system is re-solved. This process is repeated until the system is infeasible. Subsequent sets of stretched constraints may not include members from all IISs. The set of all enforced constraints contains at least one IIS with the last enforced constraint being a member of that particular IIS. Once again, the deletion filter is required to isolate a single IIS.

5. Strategies for the Integration of Filters

Chinneck devised several algorithms that combine the filters to make the search for infeasibility more efficient. The deletion filter can be used by itself to isolate an IIS. In

practice, this option is time prohibitive for many large problems, hence the deletion filter is combined with the other filters to produce better results. One strategy is to use the deletion/sensitivity filter. This filter is the basic deletion filter with the sensitivity filter applied only if the system is infeasible on a deletion iteration. Another strategy is to apply the elastic filter and upon completion apply the deletion filter. The elastic filter's output is a set which contains at least one IIS and so the deletion filter then reduces the set to contain only one IIS.

Once an IIS is identified the programmer can focus on these constraints to determine the problem and implement appropriate corrections. This study implements an algorithm using the elastic filter in conjunction with the deletion filter to isolate all the non-overlapping IISs within an infeasible integer program.

IV. AUTOMATIC SENSITIVITY ANALYSIS FOR RDA³

This chapter describes the methodology used to develop a thorough automatic sensitivity analysis of RDA³. The central focus for the analysis is the losers list introduced in Chapter I. Understandably, this list of unfunded projects is a pivotal issue and demands scrutiny. The general scheme is to attempt to force the losers one at a time into the optimal solution, re-solve the model and measure the effects. Both feasible and infeasible solutions are produced in these attempts

If forcing a loser into the solution causes infeasibility, Chinneck's algorithms are applied. Whereas Chinneck's research was motivated by the need to find data errors causing unintentional infeasibilities, the motivation for this study is to identify all the causes of infeasibility deliberately introduced. As will be shown, the identification of causes of infeasibility presents a clear story to decision makers on the tradeoffs of projects and the impact of mandated funding.

In the cases when forcing a loser into the solution maintains feasibility, the automatic sensitivity analysis presents detailed information about the resulting tradeoffs.

A. POST-OPTIMALITY ANALYSIS

Like any deterministic model, RDA³ may suffer from inexact model parameters. Hence, there exists room for error in the optimal solution based on its sensitivity to certain model parameters, such as the effectiveness coefficients assigned to each project. What can be asserted about RDA³, is that the optimal solution is a "good" one. The most preferred solution by the decision maker, can only be ascertained from a systematic, and extensive post-optimality analysis. Post-optimality analysis in linear programming may include re-

optimization, shadow price analysis, sensitivity analysis, and parametric linear programming. (Hillier and Lieberman, 1990)

1. Automatic Sensitivity Analysis

This study develops a robust sensitivity analysis methodology to the domain of the RDA³ model. The idea is to automatically provide explanatory data on unfunded projects (losers list) as well as other areas. The methodology is implemented with a GAMS program (Appendix A). An option file (Appendix B), is used to control the scope of the automatic sensitivity analysis. This file is separate from the actual analysis code and well documented, hence equipping the unsophisticated user with an easy and flexible method of directing the analysis. Additionally, features are included in the option file to enable either the analyst or decision maker to effortlessly pursue other investigative avenues that are inefficient when implemented automatically. The capability to automate the sensitivity analysis was deemed essential to RDA³'s final acceptance as a decision tool. As described earlier, the Army's modernization decision making process demands a tool that not only obtains a good solution, but also one that quickly provides a thorough tradeoff analysis with other alternatives. This tradeoff analysis is as important as the optimal solution, since it provides the decision maker insights into the dynamics of the entire decision space.

2. Areas of Interest in RDA³

This study primarily focuses on the losers list from the initial RDA³ model results. Why did a project go unfunded and what is the impact of forcing an unfunded project into the optimal solution? Some unfunded projects would clearly violate explicit constraints in the model, causing an infeasible solution, whereas others would be feasible. These feasible projects, once forced into the optimal solution, will cause other projects to leave the solution and conversely may bring other losers into the solution. The display of these causal outcomes should prove insightful to the decision makers. The most turbulent

model parameter is the annual budget level. In reality it can change daily, hence the capability of easily changing this model parameter will enable swift and responsive analysis. The budget analysis is addressed in Chapter V. Another aspect specific to the domain of RDA³ is the mandating of projects. These policy decisions are certainly subject to review, therefore a complete mandated project analysis is included.

B. IDENTIFICATION OF INFEASIBILITIES

Since RDA³ is a weighted goal program with many constraints allowed to "stretch", infeasibilities are confined to the set of inelastic constraints. An understanding of this is easily inferred from the general formulation of a goal program presented earlier in Chapter II, as well as the formulation of RDA³. Additionally, Figure 4 graphically depicts a goal (elastic constraint), A, and inelastic constraints, B and C, of a simple goal program. If the desired feasible region is assumed to be as depicted, the goal (A) will adjust with appropriate increases in the deviation variables associated with it, thus becoming feasible. Conversely, the inelastic constraint, C is inflexible and will prevent the model from achieving feasibility. Clearly, infeasibilities can only be caused by the inelastic constraints.

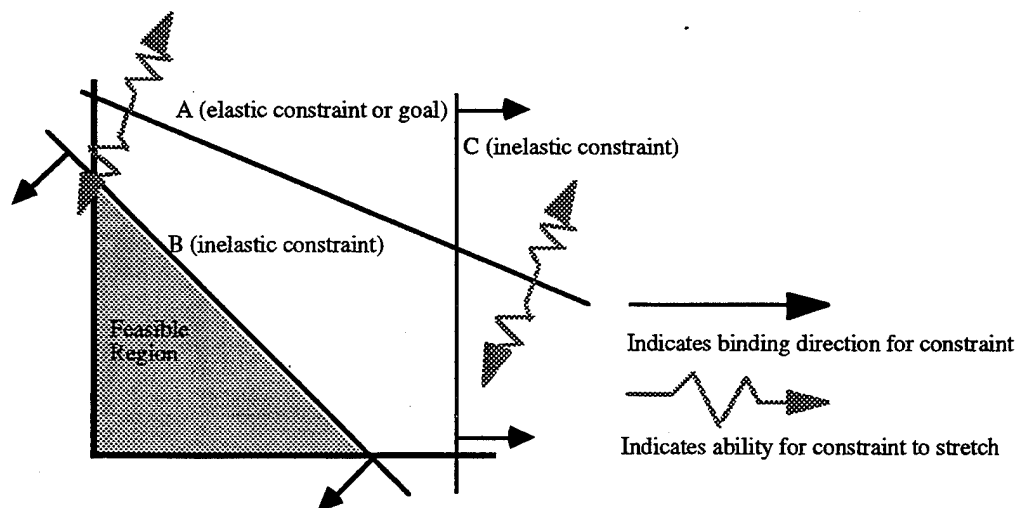


Figure 4. Infeasibility in a Goal Program

If forcing in a loser results in an infeasible solution, the decision maker may want to know which inelastic constraints are contributing to the infeasibility. Three types of inelastic constraints within RDA³ are now reviewed.

1. Budget Constraint

Equation 4.1 enforces the annual budget levels in RDA³. Forcing a loser into the solution may violate this constraint only if the sum of all the funds required by the mandated projects and the minimum funding level required by the forced in loser, exceeds the budget. This basic condition is tested for both the total funding levels and the annual funding levels. This type of infeasibility is tested without re-solving the model, thus making it efficient.

$$\sum_i \sum_j X_{ijt} \frac{ASPIRE_{ijt}}{BUDGET_t} \leq 1 ; \forall t$$

Equation 4.1

The chance of the budget constraint being violated in this way is minimal. However, given the solution from the original model, the test is very quick. RDA³ was enhanced to enable either 100% funding of mandated projects or to allow partial funding determined by the optimization. Additionally, the addition of a minimum annual funding level constraint to RDA³ further categorized the situation. Thus, the test for budget infeasibility, checks for the modus operandi and applies the appropriate evaluation. The algorithm pseudo-code for this test is shown in Figure 5.

Input: The losers list, formulation and optimal solution to RDA³

Output: Partition of losers list into budget feasible set and budget infeasible set.

```
Loop{over losers,
  Add to budget feasible set
  If minimum total aspired fraction < minimum annual funding fraction then
    If 100% funding of mandates required then
      Sum the funding for the mandates + minimum total
      aspiration for the forced in loser
      If Sum > total budget then
        Print 'Violates total budget constraint'
        Remove loser from budget feasible set
        Add loser to budget infeasible set
    Else if partial funding of mandates allowed then
      Sum the minimum funding level for the mandates +
      the minimum total aspiration for the forced in loser
      If Sum > total budget then
        Print 'Violates total budget constraint'
        Remove loser from budget feasible set
        Add loser to budget infeasible set
    }
  }
}
Loop{over years,
  If 100% funding of mandates required then
    Sum the funding for the mandates + the minimum
    funding level for the forced in loser
    If Sum > annual budget in this year then
      Print 'Violates budget constraint in this year'
      Remove loser from budget feasible set
      Add loser to budget infeasible set
  Else if partial funding of mandates allowed then
    Sum the minimum funding level for the mandates +
    the minimum funding level for the forced in loser
    If Sum > annual budget in this year then
      Print 'Violates budget constraint in this year'
      Remove loser from budget feasible set
      Add loser to budget infeasible set
  }
}
```

Figure 5. Algorithm for the Budget Test

2. Operating and Sustainment Cost (OSCOST) Constraint

The maximum operating and sustainment costs (MAXOSCOST) allowed for the entire time horizon of the analysis is enforced by Equation 4.2. Much like the budget constraint, a procedure that tests the impact of a forced-in loser and the mandated projects is necessary. Once again, the violation of this constraint is not expected, but it is easy to check, given the original model solution, and done without re-solving the model. The pseudo-code for the algorithm is identical to that shown for the budget constraint above, except total OSCOST for each project is summed and compared to the MAXOSCOST.

$$\sum_i \sum_j OSCOST_{ij} \frac{\left(\sum_t X_{ijt} \cdot ASPIRE_{ijt} \right)}{TOTASPIRE_{ij}} \leq MAXOSCOST$$

Equation 4.2

3. Logical Constraints

The more interesting sources of infeasibility are the logical constraints within RDA³. Donahue (1992) defined the logical constraints to represent the funding relationships that exist between projects. He mathematically represented these relationships using binary variables and relational operators. For instance, if project A is funded then project B must also be funded translates to Equation 4.4 in Table 7, where Z_{ij} is a binary variable equal to one if the project is funded. These relationships are dictated by either policy decisions or by physical dependencies, such as, project A is a gun and project B is the ammunition for the gun. This study expands the definition of logical constraints to include any constraint in RDA³ that contains only binary decision variables. This includes the incremental funding constraints (Equation 4.5) and the constraints that fix the binary variable for mandated projects to one (Equation 4.6). Table 7 displays the logical equations as defined by Donahue (1992) and expanded here. They are not all inclusive.

Equation Number	Logical Equation	Meaning
4.3	$Z_{ij} = Z_{i'j'}$	fund both sub-project j of project i and sub-project j' of project i' or neither
4.4	$Z_{i, "01"} \geq Z_{ij} ; \forall i, j$	fund the first sub-project of project i before other sub-projects
4.5	$Z_{ij} = 1$	must fund project i and sub-project j
4.6	$Z_{ij} + Z_{i'j'} \leq 1$	fund sub-project j of project i or sub-project j' of project i' or neither but not both
4.7	$Z_{ij} + Z_{i'j'} + Z_{i''j''} \leq 1$	fund at most one sub-project of either project i, i', i'' or none at all
4.8	$Z_{ij} = Z_{i'j'} = Z_{i''j''}$ $Z_{ij} + Z_{i''j''} \leq 1$	fund either subset {ij,i'j',i''j''} or subset {i''j''}, but not both
4.9	$2Z_{ij} - Z_{i'j'} - Z_{i''j''} \leq 0$	fund sub-project j of project i only if sub-projects j and j'' of projects i' and i'' are funded
4.10	$-2 \leq Z_{ij} - Z_{i'j'} - Z_{i''j''} \leq 0$	fund sub-project j of project i only if sub-projects j or j'' of projects i' and i'' is funded
4.11	$Z_{ij} \geq Z_{i''j''}$	if sub-project j of project i is not funded, then do not fund sub-project j'' of project i''
4.12	$2Z_{i''j''} \geq Z_{ij} + Z_{i'j'}$	if sub-project j of project i or sub-project j' of project i' is funded then must fund sub-project j'' of project i''
4.13	$Z_{i''j''} \geq Z_{ij} + Z_{i'j'} - 1$	if sub-projects j and j' of projects i and i' are funded then must fund sub-project j'' of project i''

Table 7. RDA³ Logical Constraints (from (Donahue, 1992))

C. DEVELOPMENT OF AN RDA³ SUB-MODEL FOR INFEASIBILITY TESTING

This study took advantage of the structure of RDA³ by extracting the logical constraints and formulating a sub-model to which Chinneck's infeasibility identification algorithms could be efficiently applied. The obvious advantage of this approach was the

exclusion of the majority of constraints (mainly elastic) from time consuming consideration by Chinneck's filter strategies.

1. Generic Representation of the Logical Constraints

The first step in developing the sub-model was the formulation and coding of the logical constraints in a generic form using GAMS. The reader is directed to Appendix C for a comparison of how the funding relationship constraints were formulated in the original RDA³ and how they are presently done. It was a recommended enhancement by Donahue (1992) and should clearly save time in terms of syntactical correctness. It also made possible the simple formulation of the sub-model. The 'incremental funding' constraints, mathematically shown in Equation 4.5 and the 'funding relationship' constraints are represented as GAMS equations. The 'fixing of mandated projects' constraints (Equation 4.6) are enforced by explicitly including them in the formulation.

2. Sub-model Formulation

The sub-model was formulated as an elasticized pure integer program and is shown below. In this form, Chinneck's elastic filter is easily applied. Fixing all of the elastic variables to zero converts it to the proper form for the deletion filter.

Indices:

- $lle = \{EXC1, EXC2, \dots\}$ The set of \leq funding relationship constraints
- $leq = \{COMP1, COMP2, \dots\}$ The set of $=$ funding relationship constraints
- i = The set of projects (MDEPS)
- j = The set of sub-projects (MDEP increments)

Data:

- $ALE_{lle,i,j}$ = The coefficients of Z_{ij} for constraint lle
- $AEQ_{leq,i,j}$ = The coefficients of Z_{ij} for constraint leq

- BLE_{lle} = The right hand side value for constraint lle
- BEQ_{leq} = The right hand side value for constraint leq
- k = A small scaling constant less than one

Variables:

- $INFES_{lle}$ = Elastic variable accounting for stretching in less than or equal to constraints
- $PINFES_{leq}$ = Elastic variable accounting for positive stretching in equal to constraints
- $NINFES_{leq}$ = Elastic variable accounting for negative stretching in equal to constraints
- $INCINFES_{i,j}$ = Elastic variable accounting for stretching in the incremental funding constraints
- $MPINFES_{i,j}$ = Elastic variable accounting for positive stretching in the mandated project constraints
- $MNINFES_{i,j}$ = Elastic variable accounting for negative stretching in the mandated project constraints
- $Z_{ij} = \begin{cases} 1 & \text{if sub - project } j \text{ of project } i \text{ is funded} \\ 0 & \text{otherwise} \end{cases}$

Model:

$$\begin{aligned}
& \text{Min} \sum_{lle} INFES_{lle} + \sum_{leq} (PINFES_{leq} + NINFES_{leq}) + \sum_{ij} INCINFES_{ij} \\
& + \sum_{ij} (MPINFES_{ij} + MNINFES_{ij}) + k \cdot \sum_{ij} Z_{ij} \\
\text{st. } & Z_{i, "01"} + INCINFES_{ij} \geq Z_{ij} \quad \forall i, j \\
& \sum_{ij} (ALE_{lle, i, j} \cdot Z_{ij}) - INFES_{lle} \leq BLE_{lle} \quad \forall lle \\
& \sum_{ij} (AEQ_{leq, i, j} \cdot Z_{ij}) - PINFES_{leq} + NINFES_{leq} = BEQ_{leq} \quad \forall leq \\
& Z_{ij} - MPINFES_{ij} + MNINFES_{ij} = 1 \quad \forall \text{ mandated projects} \\
& Z_{ij} = \{0, 1\} \\
& 0 \leq INFES_{lle} \leq 3 \quad \forall lle \\
& 0 \leq PINFES_{leq} \leq 3 \quad \forall leq \\
& 0 \leq NINFES_{leq} \leq 3 \quad \forall leq \\
& 0 \leq INCINFES_{ij} \leq 3 \quad \forall i, j \\
& 0 \leq MPINFES_{ij} \leq 3 \quad \forall i, j
\end{aligned}$$

3. Strategy for Identifying the Infeasibilities .

The strategy for identifying logical infeasibilities is to iteratively force one loser into the solution, and apply Chinneck's elastic filter to locate as many infeasibilities as possible. As discussed earlier, the result is a set of infeasible constraints with at least one IIS. The deletion filter is then used to either verify that only the IIS was identified, which would mean that all infeasibilities were located, or to prove the existence of other IISs. Should other IISs exist, then additional applications of the elastic/deletion filter combination are required to isolate them. On subsequent applications, the constraints of any IIS clearly identified are kept elasticized during the elastic filter process. Each application of the

elastic/deletion filter will either isolate another non-overlapping IIS or show that no more exist. A methodology for isolating overlapping IISs has not been implemented. Figure 6 is a flow chart of the strategy.

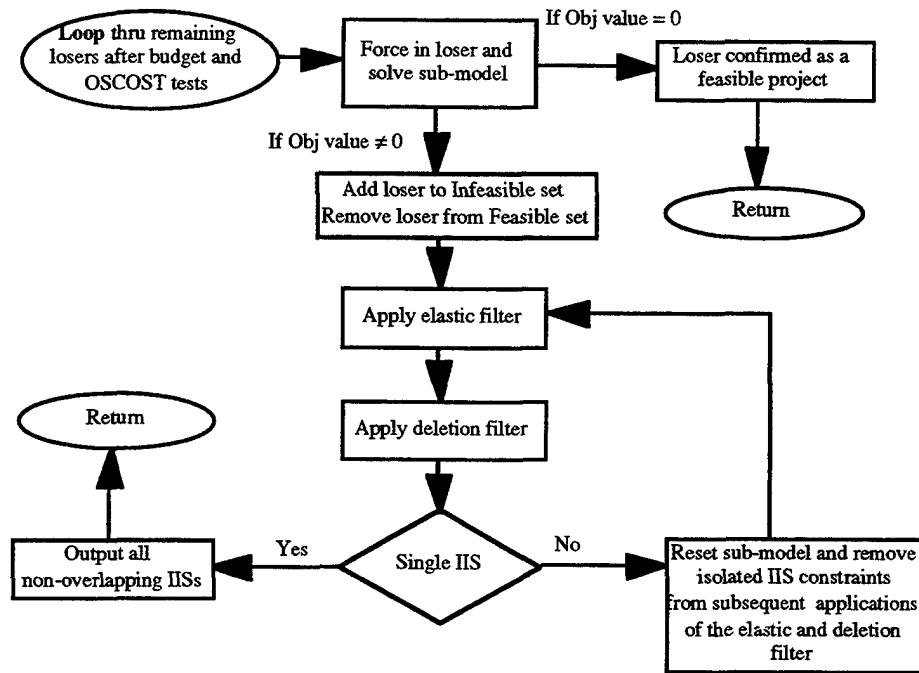


Figure 6. Flowchart for the Logical Infeasibility Identification

D. FEASIBLE PROJECT ANALYSIS

1. Single Project

The logical infeasibility identification process also specifies all of the feasible projects. Sensitivity analysis is performed by iteratively forcing them singly into the solution, re-solving the original RDA³ model and observing what happens. The decision maker and analyst want to know the effects of modifying the initial model recommendations. This study implemented an analysis that automatically determines what projects are no longer funded (forced out), as well as what losers enter the solution (followed in) as a result of the force in. Additionally, the objective function value, and the deviation variable values are produced for comparative purposes. One should be able to

compare the new objective function value with the previous one and determine the relative effect of forcing in a feasible loser. A comparison of deviation variable values should assist to pinpoint the real cause for the change. Most importantly, the decision maker will see the effects in real terms; e.g., if project A is forced in, he may find out that projects B,C,D,E,F and G are forced out (very expensive change), or he may find out that if project A is forced in that only project D is forced out. Now he may only have to compare the relative merits of the two projects to make a decision. Since the optimization for each force-in of a feasible project starts with the previous solution, the re-solving process is relatively efficient.

2. Multiple Projects

The ability to see the effect of simultaneously forcing in multiple projects into the solution is viewed as necessary and has been implemented in this study. However, it is not invoked automatically due to the combinatorially high number of options. The analyst can identify which projects to force in together in the option file. The analysis for the multiple projects is identical to the single project option.

E. MANDATED PROJECT ANALYSIS

1. Single Project

The mandated project analysis is performed very much like the feasible project analysis. Mandated projects represent policy decisions that rationally should be subject to review. The post-optimality analysis implemented here automatically studies the impact of un-mandating each of these projects, one at a time, and letting the model recommend whether they should be funded. The output is the same as for the feasible projects, highlighting those projects that enter the solution as well as those that leave. The new objective function value and goal deviations are also displayed. Congressionally mandated projects will be much more credible if it remains in the solution in this analysis.

2. Multiple Projects

Evaluating the effect of un-mandating multiple projects simultaneously is also accomplished like the feasible project analysis. Once again, the decision maker can easily direct scope of the study by manually identifying the desired mandated projects to be simultaneously un-mandated within the option file. The effects of this action are displayed as before.

V. APPLYING VARIABLE PERSISTENCE TO RDA³

As stated, the most turbulent model parameters are the annual budget figures. Two distinct situations are investigated here: when the final project selection decision has not been made and when it has. Under the first condition, the decision maker may only require the conduct of general tradeoff analysis. At that point, the annual budget analysis is just another area of interest that is finalized prior to the final decision run. To accommodate this situation, the annual budget allowances can be modified for standard sensitivity analysis.

Once a decision on the funding of projects is made, changes to the funded projects list is undesirable. Annual budget fluctuations should then only affect the funding profiles of the selected projects. A methodology is introduced to deal with this situation.

A. APPLYING PERSISTENCE TO LINEAR PROGRAMS

1. Motivation

Models are often developed to support managerial decisions that are made periodically. Capital budgeting and scheduling models are two common examples. A given capital budgeting problem may forecast investments out twenty years, however, the funding strategy is commonly scrutinized and modified periodically to account for changes in the budgeting environment. Usually, it is undesirable for small changes in the environment to cause wholesale changes in the investment strategy. Unfortunately, this is a common trait associated with linear programming (LP) models, and is believed to deter some managers from accepting LP models as decision tool alternatives. The degree to which a model maintains the previous solution from run to run is known as *persistence*. (Brown, Dell, Farmer, 1995)

2. Encouraging Persistence

To compensate for the lack of persistence in most linear programs, Professors Gerald G. Brown, Robert F. Dell, and Kevin Wood (1995) developed a methodology that enables the decision maker to control the level of persistence in a given model. Persistence is encouraged by either fixing variables, penalizing deviations from previous solutions, or by setting aspirations for constraints.

a. Variable Persistence

The most basic form of variable persistence is to simply fix variables at their previous solution values. Since this strategy may result in an infeasible solution, a more robust technique is desired. One way is to create an elastic constraint for each variable that accounts for deviation from the aspired previous solution value. The general formulation is shown below.

Data:

- α = level of persistence $0 \leq \alpha \leq 1$
- wt^+ = penalty for positive deviation from previous solution
- wt^- = penalty for negative deviation from previous solution
- X_0 = vector of the previous solution's variable values
- b' = new vector of right hand side values
- A' = new matrix of coefficients
- C' = new vector of coefficients

Variables:

- X = vector of variables
- X^+ = vector of positive deviations from X_0
- X^- = vector of negative deviations from X_0

Model:

$$\begin{aligned} & \text{Minimize } (1 - \alpha)C'X + \alpha(wt^+ \cdot X^+ + wt^- \cdot X^-) \\ & \text{s.t. } A'X = b' \\ & \quad X = X_0 + X^+ - X^- \\ & \quad X \geq 0 \\ & \quad X^+ \geq 0 \\ & \quad X^- \geq 0 \end{aligned}$$

Another method that provides a level of persistence is to place bounds on variables equal to some fraction of their previous value. This is shown below where λ is the fraction of the previous value that the current variable is allowed to under or over achieve.

Model:

$$\begin{aligned} & \text{Minimize } C'X \\ & \text{s.t. } A'X = b' \\ & \quad (1 - \lambda)X_0 \leq X \leq (1 + \lambda)X_0 \\ & \quad X \geq 0 \end{aligned}$$

b. Constraint Persistence

Persistence in an LP can also be encouraged in a similar fashion with constraints. This is done by converting constraints into goals (as in goal programming) with the aspiration or right hand side equal to the previous constraint value. Additionally, the constraints are maintained in their standard form with appropriate modifications to the coefficients and right hand sides that account for the change in the problem.

Data:

α = level of persistence $0 \leq \alpha \leq 1$

wt^+ = penalty for positive deviation from previous solution

wt^- = penalty for negative deviation from previous solution

X_0 = vector of the previous solution's variable values

b' = new vector of right hand side values

A = old matrix of coefficients

A' = new matrix of coefficients

C' = new vector of coefficients

Variables:

X = vector of variables

AX^+ = vector of positive deviations from AX_0 (over satisfaction)

AX^- = vector of negative deviations from AX_0 (under satisfaction)

Model:

Minimize $(1 - \alpha)C'X + \alpha(wt^+ \cdot AX^+ + wt^- \cdot AX^-)$

s. t. $A'X = b'$

$A'X = AX_0 + AX^+ - AX^-$

$X \geq 0$

$AX^+ \geq 0$

$AX^- \geq 0$

3. Relevance

As a capital budgeting model to be employed periodically by DCSOPS, RDA³ requires a persistence capability for general acceptance. As the prioritizer of the U.S. Army, DCSOPS is not amenable to canceling projects and starting others everytime the budget changes. This study applies the variable persistence methodology to maintain consistency of results while performing sensitivity analysis on the budget profile. It is

applied to study the impact of a budget change, while encouraging the original projects to remain in the solution.

B. SENSITIVITY ANALYSIS OF RDA³ WITH PERSISTENCE

Two variable persistence techniques were implemented. The first one fixes the funded projects into the solution and the model is re-solved. This will force the funds to be re-apportioned amongst the funded projects. If the budget outlay is increased additional projects may be funded, however, originally funded projects remain in the solution regardless of the budget change. If the solution becomes infeasible it means that the minimum funding level constraint was violated and will be identified by the previously discussed budget infeasibility test. The decision maker can then either, reduce the minimum funding level amount, or he can apply a more robust variable persistence technique.

The second variable persistence technique is the elastic constraint formulation. The variables are encouraged to remain at their previous values by elasticizing their explicit constraints and penalizing any deviation. The model formulation consists of the original RDA³ model with the following additions and modifications.

Data:

- Wt^+ = penalty for positive deviation in the Z_{ij} variables
- Wt^- = penalty for negative deviation in the Z_{ij} variables
- α = desired level of persistence
- $Z01_{ij}$ = previous solution values for the Z_{ij} variables

Variables:

- Z^+_{ij} = Accounts for the positive deviation from the Z_{ij} variables
- Z^-_{ij} = Accounts for the negative deviation from the Z_{ij} variables

Model:

$$\begin{aligned}
 & \text{Minimize } (1 - \alpha) \cdot [\text{original RDA}^3 \text{ objective function}] \\
 & \quad + \alpha \cdot \left[\sum_{ij} (Wt^+ \cdot Z_{ij}^+ + Wt^- \cdot Z_{ij}^-) \right] \\
 & \text{st. } Z_{ij} - Z_{ij}^+ + Z_{ij}^- = Z01_{ij} \quad \forall i, j \\
 & \quad \text{original RDA}^3 \text{ constraints} \\
 & \quad 0 \leq Z_{ij}^+ \leq 1 \quad \forall i, j \\
 & \quad 0 \leq Z_{ij}^- \leq 1 \quad \forall i, j
 \end{aligned}$$

The results of experiments with this formulation are reported in Chapter VI, Section F.

VI. DEMONSTRATION OF THE ANALYSIS

This chapter provides an exemplary analysis implementing the methodology introduced in Chapters IV and V. The baseline data set (Appendix H), provided by TRADOC Analysis Center, Ft. Leavenworth, Kansas, is the same one used by Donahue (1992) for the initial implementation of RDA³. It is chosen because this work is regarded as an extension of Donahue's thesis. The data set is an unclassified sample, that includes 257 projects, and covers a fifteen year programming cycle from fiscal years 1994 to 2008. The data set is modified in some places to demonstrate a particular capability introduced by this study. These modifications are indicated. Important inferences and technical aspects are highlighted for each analysis presented within this chapter. The complete output of the analyses, is in Appendices D, E, F, and G.

A. IMPLEMENTATION

As discussed earlier, this study is implemented in GAMS (Appendix A) and executable on a personal computer. Prior to initiating the automatic and directed sensitivity analysis, the RDA³ model must be run, and the RDA³ post-optimization reports must be generated. The reports program simply calculates and presents data that are useful to the decision maker, such as the percentage of budget spent and percentage of aspired funding allocated for each project. The program developed for this study, *Sensitivity Analysis for RDA³*, assimilates the information, conducts specified sensitivity analysis, and outputs summary response information to a text file. The baseline results for the automatic analyses are presented in Appendix D.

B. BUDGET, AND OPERATING AND SUPPORT COST INFEASIBILITY

This test is performed whenever either the logical infeasibility analysis, feasible project analysis, or the budget sensitivity analysis with a fixed solution is invoked. Three possible results of the analysis are demonstrated, with the data modified to create meaningful examples. However, the expected utility for this test is low, since it is highly unlikely for the budget profile to fall to the levels required to cause infeasibilities.

1. Feasible Budget and Operating and Support Cost

All of the losers for the original (baseline) RDA³ data are budget and OSCOST feasible when the mandated projects are fully funded. (Appendix D) This implies that conflicts within the logical constraints are solely responsible for infeasible losers.

2. Infeasible Budget

Four cases, depicted in Table 8, are investigated when the budget profile is infeasible, meaning it is the cause for some losers to go unfunded. For cases 1 and 2 the total budget allocation is arbitrarily lowered to \$25 billion from \$165 billion. For cases 3 and 4, FY94, FY96, FY98, FY02, and FY06 budget levels are reduced to create infeasibilities. These figures and the complete output are provided in Appendix E. The results in Table 8 show the significant affects of the full versus partial funding policy for the mandated projects. There is a sharp reduction in the number of projects that go unfunded, when the policy for mandated projects is relaxed to allow partial funding.

Case	Minimum Fraction of Total Aspired to be Funded	Minimum Annual Funding Level	Funding Policy for Mandates	# Projects Not Funded Because They Violate the Budget Constraint
1	.6 for "01" increments .8 for all others	0	Full	15
2	.6 for "01" increments .8 for all others	0	Partial	2
3	0	.75	Full	25
4	0	.75	Partial	3

Table 8. Budget infeasibility results for the baseline data with the total budget allocation reduced to \$25 billion from \$165 billion are shown in cases 1 and 2. Cases 3 and 4 investigate the effect of placing a minimum annual funding level for each project funded and reducing particular annual budget levels to cause infeasibility. It is unlikely that the budget allocation would fall to these levels. For both situations, the relaxation to partial funding for mandated projects causes a sharp reduction in the number of projects not funded due to violating a budget constraint.

3. Infeasible Operating and Support Costs

To demonstrate the purpose of this test, the maximum allowable operating and support cost was reduced to \$50 billion from \$999 billion. This level creates the desired infeasibilities for the two cases investigated in Table 9. Once again, the effect of the mandated projects funding policy is dramatic. The complete output is in Appendix E.

Case	Maximum Allowable Operating and Support Cost	Funding Policy for Mandates	# Projects Not Funded Because They Violate the Maximum Operating and Support Costs
1	\$50 Billion	Full	13
2	\$50 Billion	Partial	1

Table 9. OSCOST infeasibility results for the baseline data with the maximum allowable operating and support cost reduced to cause infeasibility. The effect of the funding policy for mandated projects is evident. There is a substantial reduction in the number of projects that are not funded because they violate the maximum allowable operating and support costs.

C. FINDING THE LOGICAL INFEASIBILITIES

This section presents the mathematical representations of all the funding relationships contained in the baseline RDA³ data, as well as the results after applying Chinneck's filters. These logical constraints, shown below, form the sub-model developed to efficiently find infeasibilities within the RDA³ data. As discussed earlier, some losers are not funded because of conflicting funding relationships (logical constraints). Although it can be done, it is no easy task to visually identify these conflicts in the sub-model. The automatic identification of many of the conflicts (infeasibilities) simplifies this process.

1. Mathematical Representation of the Funding Relationships

Mandated Projects:

$$\begin{array}{lll}
 Z_{FPEG,01} = 1 & Z_{FPJC,01} = 1 & Z_{FPSA,01} = 1 \\
 Z_{FPEL,01} = 1 & Z_{FPMK,01} = 1 & Z_{FPSA,06} = 1 \\
 Z_{FPEL,05} = 1 & Z_{FPM,01} = 1 & Z_{FPSB,01} = 1 \\
 Z_{FPFL,01} = 1 & Z_{FPNC,01} = 1 & Z_{FPWB,01} = 1
 \end{array}$$

Incremental Funding Constraints:

$$\begin{array}{lll}
 Z_{FL6V,01} \geq Z_{FL6V,02} & Z_{FPEE,01} \geq Z_{FPEE,02} & Z_{FPJC,01} \geq Z_{FPJC,02/04/06} \\
 Z_{FL6X,01} \geq Z_{FL6X,02} & Z_{FPEG,01} \geq Z_{FPEG,04} & Z_{FPLF,01} \geq Z_{FPLF,04/06} \\
 Z_{FPDA,01} \geq Z_{FPDA,02} & Z_{FPEH,01} \geq Z_{FPEH,04} & Z_{FPLG,01} \geq Z_{FPLG,02} \\
 Z_{FPDB,01} \geq Z_{FPDB,04/05/06} & Z_{FPEL,01} \geq Z_{FPEL,02/05} & Z_{FPLK,01} \geq Z_{FPLK,02/04} \\
 & Z_{FPEN,01} \geq Z_{FPEN,04} & Z_{FPMC,01} \geq Z_{FPMC,05} \\
 Z_{FPDE,01} \geq Z_{FPDE,02} & Z_{FPEP,01} \geq Z_{FPEP,06} & Z_{FPMH,01} \geq Z_{FPMH,02/03} \\
 Z_{FPDC,01} \geq Z_{FPDC,06} & Z_{FPPM,01} \geq Z_{FPPM,05} & Z_{FPMJ,01} \geq Z_{FPMJ,05} \\
 Z_{FPDH,01} \geq Z_{FPDH,04} & Z_{FPGA,01} \geq Z_{FPGA,02} & Z_{FPMK,01} \geq Z_{FPMK,04/06} \\
 Z_{FPDQ,01} \geq Z_{FPDQ,02} & Z_{FPHE,01} \geq Z_{FPHE,02/03} & Z_{FPM,01} \geq Z_{FPM,04} \\
 Z_{FPEA,01} \geq Z_{FPEA,02} & Z_{FPJA,01} \geq Z_{FPJA,02/04} & Z_{FPNE,01} \geq Z_{FPNE,02/05} \\
 Z_{FPED,01} \geq Z_{FPED,02/04} & Z_{FPJB,01} \geq Z_{FPJB,02/04/06} & Z_{FPSA,01} \geq Z_{FPSA,06}
 \end{array}$$

These equations form the constraints of the sub-model described in Chapter IV. Chinneck's filters are applied to isolate funding relationship incompatibilities for infeasible losers.

2. Baseline Results Summary

For the baseline data, 11 of 25 original losers are infeasible as a result of conflicts within the sub-model of logical constraints (Appendix D). If a constraint is identified by the elastic filter, and then not assigned to an IIS by the deletion filter, then it must belong to an overlapped IIS. The existence of several overlapped IISs were identified by the elastic filter process. The results from applying the elastic and deletion filters after forcing in project RA08,06 is shown below.

Force in: Project RA08,06 : $Z_{RA08,06} = 1$

Elastic Filter Application: The application of the elastic filter identifies at least one conflicting constraint in each IIS. Therefore, the force-in, RA08,06 is incompatible with the following funding relationships.

- $Z_{RA08,01} \geq Z_{RA08,06}$
- $Z_{FPSE,01} = Z_{RA08,01}$
- $Z_{FPSA,01} + Z_{FPSE,01} \leq 1$
- $Z_{FPSA,01} = 1$
- $Z_{FPSA,06} = 1$

Deletion Filter Application: The deletion filter then determines which of the constraints belong to one IIS. Notice that the constraint, $Z_{FPSA,06} = 1$, is not a member of the isolated IIS. This means that it is a member of an overlapped IIS. If one of the following funding relationships other than, $Z_{FPSA,01} = 1$, were removed, then RA08,06 would be feasible, and therefore could be funded.

- $Z_{RA08,01} \geq Z_{RA08,06}$
- $Z_{FPSA,01} = 1$
- $Z_{FPSA,01} + Z_{FPSE,01} \leq 1$
- $Z_{FPSE,01} = Z_{RA08,01}$

The existence of an overlapped IIS is shown above by the identification of the mandated constraint, $Z_{FPSA,06} = 1$, by the elastic filter, that is not subsequently assigned to an IIS by the deletion filter. For the relatively small set of logical constraints included in the sub-model, the analyst can easily find the offending set of constraints. For RA08,06, as well as the other infeasible losers, the analyst can now clearly communicate to its advocates precisely why it was not funded. The isolated IIS is interpreted as follows: FPSA,01 is mandated ($Z_{FPSA,01} = 1$), therefore FPSE,01 cannot be funded ($Z_{FPSA,01} + Z_{FPSE,01} \leq 1$). This implies that RA08,01 cannot be funded ($Z_{FPSE,01} = Z_{RA08,01}$), which, due to the incremental funding constraint ($Z_{RA08,01} \geq Z_{RA08,06}$), implies that RA08,06 cannot be funded. The overlapped IIS is caused by the constraint, $Z_{FPSA,01} = Z_{FPSA,06}$. In other words, the constraints, $Z_{FPSA,01} = 1$ and $Z_{FPSA,06} = 1$, are interchangeable with the isolated IIS. To fund RA08,06, the decision maker must re-define the funding relationships (logical constraints) associated with it. Only one funding relationship within each IIS needs to be removed, thus simplifying the process. At the very least, he now understands the relationship that exists between the loser and other projects and also knows exactly why it was not funded.

3. Introduction of Non-overlapped IISs

The intent of this section is to demonstrate the capability of the filter strategy implemented by this study to isolate non-overlapped IISs. First, the reader should understand that when only analyzing the losers list, forcing in one loser at a time precludes the appearance of non-overlapped IISs. Otherwise the original RDA³ data would have been infeasible. An infeasible solution for RDA³ is possible, considering the development of the numerous funding relationships may occur in an uncoordinated and disjoint fashion, and over a long period of time. Therefore, the ability to find non-overlapped IISs is essential to quickly identifying incompatible funding relationships. The original RDA³ data

becomes infeasible with the inclusion of the logical constraints (funding relationships) shown below.

$$\begin{aligned}
 Z_{FPSD,06} &= Z_{FPNC,01} \\
 Z_{FPSD,06} + Z_{FPMK,01} &\leq 1 \\
 Z_{FPNC,01} &= 1 \\
 Z_{FPMK,01} &= 1
 \end{aligned}$$

These added constraints form an IIS. The analysis performed after project RA08,06 is forced into the solution of the sub-model is shown below. Both its associated IIS, as well as the non-overlapped IIS intentionally introduced, are isolated by the filtering process. Once again, the reader should recognize the existence of a non-overlapped IIS, which is not isolated. The constraint, $Z_{FPSA,06} = 1$, is not assigned to an IIS, therefore it must be a member of an overlapped IIS.

Force in: Project RA08,06: $Z_{RA08,06} = 1$

1st Elastic Filter Application: The first application of the elastic filter identifies at least one constraint in every IIS. RA08,06 is incompatible with the following funding relationships.

- $Z_{RA08,01} \geq Z_{RA08,06}$
- $Z_{FPSE,01} = Z_{RA08,01}$
- $Z_{FPSA,01} + Z_{FPSE,01} \leq 1$
- $Z_{FPSA,01} = 1$
- $Z_{FPSA,06} = 1$
- $Z_{FPNC,01} = Z_{FPSD,06}$
- $Z_{FPMK,01} = Z_{FPSD,06}$
- $Z_{FPMK,01} = 1$
- $Z_{FPNC,01} = 1$

1st Deletion Filter Application: This filter isolates the following set of constraints, that together form an IIS and are incompatible with RA08,06. The order in which constraints were tested by this filter, dictated the first IIS to be isolated. It turns out to be the one intentionally introduced. The

decision maker can fix the infeasibility in the RDA³ data by studying these constraints and removing one or more that do not make sense. The constraints of this IIS are removed from the sub-model prior to searching for other IISs.

- $Z_{FPMK,01} = 1$
- $Z_{FPMK,01} = Z_{FPSD,06}$
- $Z_{FPNC,01} = 1$
- $Z_{FPNC,01} = Z_{FPSD,06}$

2d Elastic Filter Application: At least one constraint in any remaining IIS is identified by this filter. Notice that all of the constraints were already identified by the first elastic filter application.

- $Z_{RA08,01} \geq Z_{RA08,06}$
- $Z_{FPSA,01} = 1$
- $Z_{FPSE,01} = Z_{RA08,01}$
- $Z_{FPSA,06} = 1$
- $Z_{FPSA,01} + Z_{FPSE,01} \leq 1$

2d Deletion Filter Application: The remaining non-overlapped IIS is isolated. Once again, notice that the constraint, $Z_{FPSA,06} = 1$, is not assigned to an IIS and therefore belongs to an overlapped IIS. As demonstrated earlier, by locating logical constraints that contain FPSA,06, the analyst can determine the set of constraints that form this additional infeasible set of constraints. Forcing RA08,06, not only identified its associated IISs, but also identified the non-overlapped IIS that made the RDA³ data infeasible.

- $Z_{RA08,01} \geq Z_{RA08,06}$
- $Z_{FPSE,01} = Z_{RA08,01}$
- $Z_{FPSA,01} + Z_{FPSE,01} \leq 1$
- $Z_{FPSA,01} = 1$

To locate the infeasibility in the original data, the loser forced in need not be an infeasible loser. If a feasible loser were forced in, the only isolated IIS would be the one that causes infeasibility in the original data.

D. MANDATED PROJECT ANALYSIS

Table 10 summarizes the analysis performed on the mandated projects that are members of an IIS. For the baseline model, there are four mandated projects that contribute to infeasibilities. From the specific results (Appendix D), one can see the effect of un-mandating these projects one at a time. Not only can one see the change in the budget allocation to the un-mandated project, but also the effect in real terms. How many projects are forced out of the solution and how many projects enter the solution as a result of the action. Credibility is strengthened for projects with no change to the solution or funding profile, such as FPSA,01 and FPSB,01. On the other hand, a mandated project may be questionable if it leaves the solution, such as FPEL,05.

This analysis can be repeated for all of the mandated projects as well. Results for this are located in Appendix F. Table 11 shows the results of simultaneously un-mandating the same 4 mandated projects that were members of an IIS. To see the effect of un-mandating all of the mandated projects, the analyst should re-solve RDA³ with the partial-funding-for-mandates policy in effect.

Mandated Projects	# Projects Forced-out	# Projects Enter	% Funding Before	% Funding After	Objective Function
FPEL,05	16	5	100	0	889.88
FPSA,01	0	0	100	100	919.63
FPSA,06	0	0	100	80	916.65
FPSB,01	0	0	100	100	919.63

Table 10. Summary information after un-mandating those mandated projects that are incompatible with one or more losers. Credibility is gained when the funding level remains the same after un-mandating, as with FPSA,01. FPEL,05 deserves more scrutiny since it is no longer funded.

Mandated Projects	# Projects Forced-out	# Projects Enter	% Funding Before	% Funding After	Objective Function
Group Effect	19	10	n/a	n/a	799.03
FPEL,05	n/a	n/a	100	0	n/a
FPSA,01	n/a	n/a	100	0	n/a
FPSA,06	n/a	n/a	100	0	n/a
FPSB,01	n/a	n/a	100	100	n/a

Table 11. Summary information after un-mandating a group of mandated projects. The motivation for which ones to test is strictly up to the analyst. In this case, three leave the solution and one remains. Notice that the objective function value is greatly improved from the original value of 919.63.

E. FEASIBLE PROJECT ANALYSIS

There are 14 feasible losers in the baseline data. Forcing each feasible loser into the solution, one at a time, provides some very interesting results (Table 12). For example, FPJB,06, FPLF,06, FPLG,02, FPLK,04, FPMM,04, and FPNE,05, can each enter the solution without causing any other projects to forced out or following in. The results of this test reflects the tradeoffs for the feasible losers to become selected and in each case the scope of the problem is substantially reduced. For a project such as, FPSD,01, the

tradeoff involves five previously selected projects. Therefore, instead of comparing FPSD,01 with every other project, the decision maker need only consider the merits of the five projects that leave the solution. This process enables the decision maker to more easily understand the complete dynamics of the problem. In the case of project, FPLK,02, the tradeoff involves only two previously selected projects. The decision maker can readily compare the merits of the loser with these two projects and determine a course of action.

Forced in Projects	# Projects Forced-out	# Losers Following in	Objective Function
FL6X,01	2	3	921.67
FL6X,02	2	3	921.67
FPHB,01	2	3	921.67
FPJB,06	0	0	920.50
FPLF,06	0	0	920.88
FPLG,02	0	0	919.74
FPLK,02	2	0	919.96
FPLK,04	0	0	921.06
FPM,04	0	0	921.38
FPNB,01	2	0	960.72
FPNE,05	0	0	920.30
FPSD,01	5	1	1110.85
FPSD,04	5	2	1111.27
FPSD,06	5	1	1110.85

Table 12. Summary information after forcing in feasible losers one at a time. Five projects do not cause project to be either forced-out or to follow-in. They can individually be funded with the current budget profile.

The summary results of forcing in a group of feasible losers is shown in Table 13 with the complete results located in Appendix F. The previous analysis demonstrated that the three projects chosen are able to individually enter the solution. When all three are

simultaneously forced-in, only one project is forced out of the solution. In this case, the value (warfighting value) of the project forced-out is only marginally better than the losers. Thus, the decision maker may decide to fund the three project option vice the one project option.

Forced in Projects	# Projects Forced-out	# Losers Following in	Objective Function
FPJB,06 FPLF,06 FPM,04	1	0	924.28

Table 13. Summary information after forcing in a group of feasible projects. The one project forced-out has only a marginally better value than those forced-in, thus indicating a potentially desirable change.

F. BUDGET SENSITIVITY ANALYSIS

The most turbulent model parameter, budget level, is studied in this section. To demonstrate the versatility of the application of variable persistence, both feasible and infeasible budget profiles are investigated. An infeasible budget profile is defined as a profile that is not sufficient to fund all of the projects under consideration. The detailed analysis is presented in Appendix G. For each budget situation, three different models were solved: *Model 1-RDA*³ with no changes except budget levels, *Model 2-RDA*³ with the originally funded projects fixed, and *Model 3-RDA*³ with a robust variable persistence applied. Summary results are shown in Tables 14 and 15.

Model	Total Budget Allocation	# Projects Forced-out of the solution	# Losers that Enter the Solution	% Total Budget Spent	Objective Function Value
Original RDA ³	\$165 billion	n/a	n/a	95.89	919.63
1. Re-solved RDA ³	\$135 billion	21	0	99.88	1044.55
2. Original Solution Fixed	\$135 billion	0	0	100	1118.02
3. Persistence Applied	\$135 billion	0	0	100	1118.02

Table 14. Summary of the budget sensitivity analysis with a feasible budget profile. Model 1, cause a wholesale change in funded projects, but achieves a better objective function value than Models 2 and 3.

Model	Total Budget Allocation	# Projects Forced-out of the solution	# Losers that Enter the Solution	% Total Budget Spent	Objective Function Value
Original RDA ³	\$165 billion	n/a	n/a	95.89	919.63
1. Re-solved RDA ³	\$120 billion	27	3	97.84	1060.41
2. Original Solution Fixed	\$120 billion	n/a	n/a	n/a	Infeasible
3. Persistence Applied	\$120 billion	1	0	100	1354.31

Table 15. Summary of the budget sensitivity analysis with an infeasible budget profile.

This study shows that Model 3 provides the same solution as Model 2 with a feasible budget profile (Table 14) and is more robust since it also provides a solution when Model 2 is infeasible (Table 15). The model of choice, Model 1 or Model 3, depends on the decision maker's priorities. As discussed previously, before the final decision has been made, the budget allocation is just another parameter of interest where sensitivity analysis can be applied. The projects have not been chosen and therefore, the model that provides the best objective function value may be the desired one. To maximize the objective function value, Model 1 is preferred for the sensitivity analysis, regardless of the budget situation. On the other hand, if the project selection has been made, and the budget profile

changes, Model 3 is more suitable to for the conduct of sensitivity analysis. Model 3 minimizes change. Tables 14 and 15 show that when the budget profile changes Model 1 produces a wholesale change in project selection, whereas, change is minimized with Model 3. There is a tradeoff for minimizing change. In the infeasible budget profile scenario, further investigation shows that the funding turbulence under the Model 3 solution is worsened (Appendix G). This may be significantly outweighed by the decision maker's priorities and at worst provides him with options. The level of persistence applied could be reduced, thus allowing the decision maker to seek a balance between limiting change and achieving capital budgeting goals.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

RDA³, by itself, is a useful decision tool. It rapidly assimilates data and provides an optimal mix of research projects and an optimal allocation of scarce research and development dollars. However, this may not be sufficient information to make a decision concerning billions of dollars. This study develops and implements a GAMS formulation, *Sensitivity Analysis for RDA³*, that automatically investigates a great portion of the decision space. After running this program, the decision maker understands the tradeoffs involved with unfunded projects, and in some cases determines that some losers could in fact be funded. Policy decisions, which include the mandating of projects as well as the funding relationships (logical constraints), are thoroughly reviewed. For the baseline data in this study, most of the mandated projects gained credibility through this review, but there were a few that deserve further scrutiny. For those losers that are not funded due to conflicts in the funding relationships, a clear story is presented that articulates precisely what the conflicts are. In every case, the scope of the problem for each loser is dramatically reduced, thus allowing the decision maker to compare the merits of projects on a remarkably small scale.

Additionally, a manually directed sensitivity analysis of the budget is possible. In today's environment it is increasingly necessary to study the impact of sharp reductions in research and developments dollars. *Sensitivity Analysis for RDA³*, provides a robust capability to accomplish this in a way that is consistent with the decision maker's priorities. The decision maker can maximize the achievement of his capital budgeting goals, minimize

the change to the current set of research projects, or seek a balance between achievement and change.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Development of a Graphical User Interface (GUI)

The development of a GUI for RDA³ was proposed by Donahue (1992) and continues to be an obvious enhancement. Any enhancement that makes the process easier for the decision maker, as well as the analyst with no GAMS training, is desirable. An initial step towards the development of a GUI would be the integration of RDA³ and Sensitivity Analysis for RDA³ with a standard spreadsheet. Although the intent of this study is to make the sensitivity analysis as simple as possible, there is still the requirement for directions to be given in GAMS syntax.

2. Obtaining Project Effectiveness Coefficients

As discussed earlier, the methodology currently used to obtain the project effectiveness coefficients is the controversial Analytic Hierarchy Process (AHP). Another value assessment methodology based on elicitation procedures, such as SMARTS or SMARTER should be pursued (Edwards and Barron, 1994). Presently, research is underway to find another methodology at the Concepts Analysis Agency (CAA) (Loerch, 1995).

3. Implementation of a Heuristic to Isolate Overlapped IISs

This study implemented a strategy to find non-overlapped irreducible inconsistent sets. Since the existence of overlapped IISs is more prevalent, a heuristic designed to find as many of them as possible would be useful. If overlapped IISs exist, the first constraints identified by the elastic filter process should be members of overlapped IISs. This is because the objective of the elastic filter is to minimize the sum of the elastic variables that

indicate infeasibility. Therefore, any constraint that is a member of more than one IIS should be discovered on the first pass of the elastic filter.

C. RELEVANCE TO THE ARMY

The usefulness of this study is directly linked to RDA³'s adoption as a capital budgeting tool for the United States Army. If DCSOPS decides to use RDA³ in the development of the Army Modernization Plan, then the integration of *Sensitivity Analysis for RDA³* will substantially enhance the analysis. Otherwise, the Army should consider providing a similar automatic sensitivity analysis capability to whatever model is used. Further research and commitment to automating the analysis could potentially streamline the interactive process between decision makers and analysts, and accelerate the overall decision cycle.

APPENDIX A. GAMS FORMULATION

The GAMS formulation for *Sensitivity Analysis for RDA³* is presented below.

```

$TITLE Sensitivity Analysis for RDA3
$onmixed offsymxref offsymlist offuellist
*-----
*           Summary Report of the Losers List
*-----
OPTIONS
  limrow   =      0
  limcol   =      0
  solprint =    OFF
  mip      =     XA
  rmip     =     XA
  optcr    =    0.05
  optca    =      0
  iterlim  =   50000
  reslim   =   10000
  integer1 =    101
  integer2 =    122
;
*-----
$INCLUDE RDA3.OPT

ALIAS (I,II,III);
ALIAS (J,JJ,JJJ);
ALIAS (LLE,LLE1);
ALIAS (LEQ,LEQ1);

SET ELASTICNUM Loop index for number of logical equations /1*100/;
ALIAS (ELASTICNUM,IISNUM);

SET LOS(I,J) The original set of losers;
  LOS(IJ)=YES$(Z.L(IJ) EQ 0);

SET LOS1(I,J) The set of losers after unfunded MDEP forced in;
SET FORCEOUT(I,J) Set of increments that are forced out;
SET FOLLOWIN(I,J) Set of increments that follow a forced-in increment;

SET FEASIBLE(I,J) The set of losers that do not violate absolute constraints;
  FEASIBLE(IJ)=LOS(IJ);

SET INFEASIBLE(I,J) The set of losers that are infeasible due to ;
*           constraint violations;
  INFEASIBLE(I,J)=NO;

SET MANDATED(I,J) The temporary set of mandated MDEPs that conflict with a given force
in;
  MANDATED(IJ)=NO;

SET MANDCON(I,J) The permanent set of all mandated MDEPs that conflict with a force
in;
  MANDCON(IJ)=NO;

```

```

SET INCIIS(I,J) The set of INCREMENT equations that are a part of an isolated IIS;
    INCIIS(IJ)=NO;

SET LLEIIS(LLE) The set of LOGCLE equations that are a part of an isolated IIS;
    LLEIIS(LLE)=NO;

SET LEQIIS(LEQ) The set of LOGCEQ equations that are a part of an isolated IIS;
    LEQIIS(LEQ)=NO;

SET MANIIS(I,J) The set of MANDATES equations that are a part of an isolated IIS;
    MANIIS(IJ)=NO;

SET MANON(I,J) MANDATES equation inclusion switch;
    MANON(IJ(I,J))$(TOTASPIRE(I,J) AND(MANDATE(I,J) EQ 1))= YES;

SET MANON2(I,J) Copy of MANON switch;
    MANON2(IJ)$MANON(IJ) = YES;

SET INCOFF(I,J) Set of INCREMENT equations turned off;
    INCOFF(IJ)= NO;

SET MANOFF(I,J) Set of MANDATE equations turned off;
    MANOFF(IJ)= NO;

SET LLEOFF(LLE) Set of LOGCLE equations turned off;
    LLEOFF(LLE)= NO;

SET LEQOFF(LEQ) Set of LOGCEQ equations turned off;
    LEQOFF(LEQ)= NO;

PARAMETERS
    XO1(I,J,T) Original optimal value of X
    ZO1(I,J) Original optimal value of Z
    NWARVALO1 Original optimal value of NWARVAL
    NBAL1O1 Original optimal value of NBAL
    NBAL2O1 Original optimal value of NBAL2
    PBAL1O1 Original optimal value of PBAL1
    PBAL2O1 Original optimal value of PBAL2
    NTURBO1 Original optimal value of NTURB
    DEVIATO1 Original optimal value of DEVIATION;

XO1(IJ,T) = X.L(IJ,T);
ZO1(I,J) = Z.L(I,J);

NWARVALO1 = SUM(T,NWARVAL.L(T));
NBAL1O1 = SUM((K,T),NBAL1.L(K,T));
NBAL2O1 = SUM((K,T),NBAL2.L(K,T));
PBAL1O1 = SUM((K,T),PBAL1.L(K,T));
PBAL2O1 = SUM((K,T),PBAL2.L(K,T));
NTURBO1 = SUM((IJ,T),NTURB.L(IJ,T));
DEVIATO1 = DEVIATION.L;

PARAMETERS
    NEWFUND Funding for un-mandated MDEP
    NEWPERC Percent funding for un-mandated MDEP
    ;

PARAMETERS
    COUNT Global Counter
    FLAG Global Flag

```

TESTNUM Counter for the number of the sensitivity test
 BUDGTNUM Counter for the number of the budget test
 LOGICNUM Counter for the number of the logical infeasible test
 LOGCFLAG Flag that indicates whether or not logical infeasibilities exist
 MANDNUM Counter for the number of the mandate analysis
 FEASNUM Counter for the number of the feasible test;

TESTNUM = 0;
 BUDGTNUM = 0;
 LOGICNUM = 0;
 MANDNUM = 0;
 FEASNUM = 0;
 COUNT = 0;
 LOGCFLAG = 0;
 FLAG = 0;

PARAMETERS

TNWARVAL Total negative warvalue deviation
 TNBAL1 Total negative balance deviation from desired
 TNBAL2 Total negative balance deviation from minimum
 TPBAL1 Total positive balance deviation from desired
 TPBAL2 Total positive balance deviation from maximum
 TNTURB Total negative turbulence deviation
 TDEVIATION Total deviation for model
 ;

TNWARVAL = SUM(T,NWARVAL.L(T));
 TNBAL1 = SUM((K,T),NBAL1.L(K,T));
 TNBAL2 = SUM((K,T),NBAL2.L(K,T));
 TPBAL1 = SUM((K,T),PBAL1.L(K,T));
 TPBAL2 = SUM((K,T),PBAL2.L(K,T));
 TNTURB = SUM((IJ,T),NTURB.L(IJ,T));

TDEVIATION = DEVIATION.L;

*-----

*For budget analysis

PARAMETERS

NTOTFUN(i,j) total funding allocated to
 mdep increment
 NMISNFUN(k,t) funding given to mission area by
 fiscal year
 NTOTYEAF(t) total funding by fiscal year
 NTOTYEAA(t) total funding aspired by fiscal year
 NTOTMISF(k) total funding given to mission area
 NTOTMISA(k) total funding aspired by mission
 area
 NTOTAS total funding requested
 NTOTSPEN total funding allocated
 NTOTBUDGE total budget
 NFUNDPER(i,j,t) percentage funded for each MDEP
 NFUNDMONE(i,j,t) dollars Funded for each MDEP

 NPERCFUNA(I,J) percentage of aspiration funded
 NPCTFUNM(K) percentage of mission area aspiration
 funded
 NPCTBUDGEM(K) percentage of budget spent per mission
 area
 NPCTALLOM(K) percentage of funds spent allocated per
 mission area
 NOVERALPCA overall percentage of aspired funds spent
 NOVERALPCB overall percentage of budget spent

```

NPCTUNSPB      percentage of budget that is unspent
NSUMASPIR      sum of all aspired funds for MDEPs
NSUMFUN        sum of all actual funds for MDEPs
NPCTFUNA       percentage of aspired funds actually funded
NSUMFUNW       total warvalue provided by funded MDEPs
NSUMFUNO       total operating cost for funded MDEPs
NEXCASPIR      total aspired for excluded MDEPs
NEXCNU         number of excluded MDEPs
NEXCWARVA      total warvalue for excluded MDEPs
;
*-----
*Output file settings

FILE LOST/LOST.DAT/;
PUT LOST;
LOST.PC= 3;
LOST.PW= 200;
LOST.ND= 2;
LOST.TM= 1;
LOST.PS= 55;
LOST.NJ= 2;
*-----
*Title
PUTTL SYSTEM.DATE,' ',SYSTEM.TIME,@65,'Page ',SYSTEM.PAGE//
      @17,'AUTOMATIC SENSITIVITY ANALYSIS FOR RDA3'/
      @17,'_____''//';

PUT@5,'This program was developed by CPT Pete Johnson in partial'/
      @5,'fulfillment of the requirements for a Master of Science in'/
      @5,'Operations Research at the Naval Postgraduate School, Monterey,'/
      @5,'California. His thesis advisor was Professor Richard E. Rosenthal.'//;

PUTPAGE;
LOST.TLLL= 0;
PUTTL SYSTEM.DATE,' ',SYSTEM.TIME,@65,'Page ',SYSTEM.PAGE//;
*-----
*Check to see if a loser MDEP breaks the budget in any given year for
*either a 100% funding policy or a partial funding policy of mandated
*projects.

PARAMETER MANDCOST(T) lower bound on cost of mandated projects in year t ;

MANDCOST(T) = SUM((II,JJ) $ MANDATE(II,JJ),
      ASPIRE(II,JJ,T) * (1$FULL+MINLEVYR(II,JJ)$ (FULL EQ 0))) ;

PARAMETER MANDOSCOST lower bound on oscost of mandated projects ;

MANDOSCOST = SUM( (II,JJ) $ MANDATE(II,JJ),
      OSCOST(II,JJ) * (1$FULL+MINLEVYR(II,JJ)$ (FULL EQ 0))) ;

PARAMETER MANCOST lower bound on cost of mandated projects if minlevel
* greater than minlevyr
;

MANCOST = SUM((II,JJ)$MANDATE(II,JJ),
      TOTASPIRE(II,JJ)*(1$FULL+MINLEVEL(II,JJ)$ (FULL EQ 0)));

IF[LOGICAL OR FEASIBL OR GROUPFES,

TESTNUM=TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Budget and OSCOST Feasibility Analysis'/

```

```

@5, '_____';

PUT @5, 'Budget profile: ';
LOOP[T, PUT @24, T.TL:<5:0, BUDGET(T):<20:0//;
]; {loop}
PUT/@5, 'Maximum total OSCOST: ', @29, MAXOSCOST:<20:0//;

PUT @5, 'Result: ';

LOOP[(I,J)$FEASIBLE(I,J),
  IF[MINEVYR(I,J) LT MINLEVEL(I,J),
    {then}
      IF[ ( MINLEVEL(I,J)*TOTASPIRE(I,J) + MANCOST
          GT TOTBUDGET),
        {then}
          COUNT= COUNT + 1;
          BUDGTNUM$(COUNT EQ 1)= BUDGTNUM +1;

          PUT$(COUNT EQ 1) @14, BUDGTNUM:>2:0, '.';
          PUT$(COUNT EQ 1) @18, I.TE(I):27, I.TL:4, J.TL:2/
            @18, 'Violates the total budget constraint ';

          FEASIBLE(I,J)=NO;
          INFEASIBLE(I,J)=YES;
        ]; {if}
      ]; {if}

    LOOP[T, {if true then violates the annual budget constraint}
      IF[ ( MINEVYR(I,J)*ASPIRE(I,J,T) + MANDCOST(T)
          GT BUDGET(T)),
        {then}
          COUNT= COUNT + 1;
          BUDGTNUM$(COUNT EQ 1)= BUDGTNUM +1;

          PUT$(COUNT EQ 1) @14, BUDGTNUM:>2:0, '.';
          PUT$(COUNT EQ 1) @18, I.TE(I):27, I.TL:4, J.TL:2/
            @18, 'Violates the budget constraint in year: ';
          PUT @60, T.TL//;

          FEASIBLE(I,J)=NO;
          INFEASIBLE(I,J)=YES;
        ]; {if}
      ]; {loop}

    IF[COUNT NE 0,
      {then}
        PUT//;
      ]; {if}

    *-----
    *check adherence to maximum OSCOST

    {if true then does not adhere to the maximum OSCOST}
    IF[ MANDOSCOST + OSCOST(I,J) * MAX(MINEVYR(I,J), MINLEVEL(I,J))
      GT MAXOSCOST,
      {then}
        BUDGTNUM$(COUNT EQ 0)= BUDGTNUM +1;
        PUT$(COUNT EQ 0) @14, BUDGTNUM:>2:0, '.';
        PUT$(COUNT EQ 0) @18, I.TE(I):27, I.TL:4, J.TL:2//;
        PUT @18, 'Does not adhere to the maximum operation and support costs.'//;

```

```

        FEASIBLE(I,J)=NO;
        INFEASIBLE(I,J)=YES;
    ]; {if}
    COUNT=0;
]; {loop}

LOOP[(I,J)$INFEASIBLE(I,J),
    COUNT=COUNT+1;
]; {loop}
IF[COUNT EQ 0, PUT @14,'All losers are budget and OSCOST feasible'///;
]; {if}

BUDGTNUM= 0; {re-initialize counter}
COUNT= 0; {re-initialize counter}
PUTPAGE;
LOST.HDLL= 0;

]; {logical or feasibl or groupfes}
*-----
*Develop a sub-model including only the logical constraints
*and the INCREMENT equations from RDA3.

VARIABLES
    ELASTICS Equal to sum of the elastic variables in sub-model
    ELASTIC Objective function variable for sub-model;

POSITIVE VARIABLES
    MNINFES(I,J) Elastic variable accounting for negative infeasibility
    MPINFES(I,J) Elastic variable accounting for positive infeasibility;

EQUATIONS
    LOGICDEF1
    LOGICDEF
    MANDATES(I,J);

*Explicitly include the mandated variables as equations in the sub-model
*First relax the mandated variables

Z.LO(IJ(I,J))$(TOTASPIRE(I,J) AND (MANDATE(I,J) EQ 1))= 0;

MANDATES(IJ(I,J))$MANON(I,J)..
    Z(I,J)-MPINFES(I,J) +MNINFES(I,J)=E=1.0;

LOGICDEF1..ELASTICS=E=SUM(LLE,INFES(LLE))
    +SUM(LEQ,PINFES(LEQ)+NINFES(LEQ))
    +SUM(IJ(I,J)$((ORD(J) GT 1)$IJ(I,"01")),INCINFES(I,J))
    +SUM(IJ(I,J),MNINFES(I,J) +MPINFES(I,J));

LOGICDEF..ELASTIC=E= ELASTICS +.01*SUM(IJ,Z(IJ));

MODEL LOSER/LOGICDEF,LOGICDEF1,INCREMENT,LOGCLE,LOGCEQ,MANDATES/;
    {submodel of all logical constraints}

MODEL DELETION/LOGICDEF,LOGICDEF1,INCREMENT,LOGCLE,LOGCEQ,MANDATES/;
    {submodel of all logical constraints}

*-----
*Initial bounds for the elastic variables

INFES.LO(LLE)=0;

```



```

PINFES.LO(LEQ)=0;
NINFES.LO(LEQ)=0;
INCINFES.LO(IJ)=0;
MNINFES.LO(IJ)=0;
MPINFES.LO(IJ)=0;

INFES.UP(LLE)=3;
PINFES.UP(LEQ)=3;
NINFES.UP(LEQ)=3;
INCINFES.UP(IJ)=3;
MNINFES.UP(IJ)=3;
MPINFES.UP(IJ)=3;
*-----
*Perform infeasibility test on all losers

IF[ LOGICAL, {then}

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Logical Constraint Infeasibility Analysis'//
@5,'_____''//';
*-----
*Analyze each loser still feasible by forcing into the solution one at a time

LOOP[ (II,JJ)$FEASIBLE(II,JJ),

Z.FX(II,JJ)=1.0;
SOLVE LOSER USING MIP MINIMIZING ELASTIC;

{infeasible if elastic variables have value}
IF [ ELASTICS.L NE 0, {then}
LOGICNUM= LOGICNUM +1;
LOGCFLAG= 1.0;
PUT @5,LOGICNUM:>2:0,'.';
PUT @9,'Infeasible loser: ';
PUT I.TE(II):27,II.TL:4,JJ.TL:2//;

FEASIBLE(II,JJ)=NO;
INFEASIBLE(II,JJ)=YES;
*-----
*Perform elastic filtering of the submodel LOSER
LOOP[IISNUM$(ELASTICS.L NE 0),

COUNT= COUNT +1.0;
PUT @5,'Filter pass #',COUNT:<3:0//;
PUT @9,'Constraints Violated: '//;

LOOP[ ELASTICNUM$(LOSER.modelstat NE 4),

*Test the less than or equal to constraints for infeasibilities

LOOP[ LLE$(INFES.L(LLE) NE 0),

PUT @9,LLE.TL:7,', Fund either but not both: ';

LOOP[ (III,JJJ)$ALE(LLE,III,JJJ),
PUT @42,I.TE(III):27,III.TL:4,JJJ.TL:2//;
MANDATED(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
MANDCON(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
]; {loop}
PUT//;

```

```

    INFES.FX(LLE)=0;
    LLEIIS(LLE)=YES;
]; {loop}

*Test the equal to constraints for infeasibilities

LOOP[ LEQ$( (NINFES.L(LEQ) NE 0) OR (PINFES.L(LEQ) NE 0)),
    FLAG= 1;
    PUT @9,LEQ.TL:7,', Fund both or neither: ';

    LOOP[ (III,JJJ)$AEQ(LEQ,III,JJJ),
        PUT @38,I.TE(III):27,III.TL:4,JJJ.TL:2/;
        MANDATED(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
        MANDCON(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
    ]; {loop}

    NINFES.FX(LEQ)=0;
    PINFES.FX(LEQ)=0;
    LEQIIS(LEQ)=YES;
]; {loop}

    IF[FLAG, {then}
        PUT/;
    ]; {if}
    FLAG=0;

*Test the INCREMENT equations for infeasibilities

LOOP[ (III,JJJ)$ (INCINFES.L(III,JJJ) NE 0),
    FLAG= 1;
    PUT @9,'Must fund ',III.TL:4,"01 before "
        I.TE(III):27,III.TL:4,JJJ.TL:2/;

    MANDATED(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
    MANDCON(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
    INCINFES.FX(III,JJJ)=0;
    INCIIS(III,JJJ)=YES;
]; {loop}

    IF[FLAG, {then}
        PUT/;
    ]; {if}
    FLAG=0;

*Test the MANDATES equations for infeasibilities

LOOP[ (III,JJJ)$ ( (MNINFES.L(III,JJJ) NE 0) OR
    (MPINFES.L(III,JJJ) NE 0)),
    FLAG=1;
    PUT @9,'Mandated: Must fund ',I.TE(III):27,III.TL:4,JJJ.TL:2/;
    MANDATED(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
    MANDCON(III,JJJ)$ (MANDATE(III,JJJ) EQ 1)=YES;
    MNINFES.FX(III,JJJ)=0;
    MPINFES.FX(III,JJJ)=0;
    MANIIS(III,JJJ)=YES;
]; {loop}

    IF[FLAG, {then}
        PUT/;
    ]; {if}
    FLAG=0;

```

```

        SOLVE LOSER USING MIP MINIMIZING ELASTIC;

]; {loop, ELASTICNUM}

$ontext
    LOOP[(III,JJJ)$MANDATED(III,JJJ),

        PUT @9,'*Mandated: ',I.TE(III):27,III.TL:4,JJJ.TL:2/;
        MANDATED(III,JJJ)= NO;
    ]; {loop}
$offtext
*-----
* Apply the Deletion Filter
*Delete all the constraints from Model Loser except for those isolated by the
*elastic filter.

LOOP[(III,JJJ)$ (NOT(INCIIS(III,JJJ))),
    INCON(III,JJJ)=NO;
]; {loop}

LOOP[(III,JJJ)$ (NOT(MANIIS(III,JJJ))),
    MANON(III,JJJ)=NO;
]; {loop}

LOOP[LLE1$(NOT(LLEIIS(LLE1))),
    LLEON(LLE1)=NO;
]; {loop}

LOOP[LEQ1$(NOT(LEQIIS(LEQ1))),
    LEQON(LEQ1)=NO;
]; {loop}

*Remove constraints one at a time and test infeasibility

LOOP[(III,JJJ)$INCIIS(III,JJJ),
    INCON(III,JJJ)=NO;
    SOLVE DELETION USING MIP MINIMIZING ELASTIC;

    IF[DELETION.modelstat NE 4, {then}
        INCON(III,JJJ)=YES;
    ELSE
        INCIIS(III,JJJ)=NO;
    ]; {if}
]; {loop}

LOOP[(III,JJJ)$MANIIS(III,JJJ),
    MANON(III,JJJ)=NO;
    SOLVE DELETION USING MIP MINIMIZING ELASTIC;

    IF[DELETION.modelstat NE 4, {then}
        MANON(III,JJJ)=YES;
    ELSE
        MANIIS(III,JJJ)=NO;
    ]; {if}
]; {loop}

LOOP[(LLE1)$LLEIIS(LLE1),
    LLEON(LLE1)=NO;
    SOLVE DELETION USING MIP MINIMIZING ELASTIC;

```

```

        IF[DELETION.modelstat NE 4, {then}
            LLEON(LLE1)=YES;
        ELSE
            LLEIIS(LLE1)=NO;
        ]; {if}
    ]; {loop}

    LOOP[(LEQ1)$LEQIIS(LEQ1),
        LEQON(LEQ1)=NO;
        SOLVE DELETION USING MIP MINIMIZING ELASTIC;

        IF[DELETION.modelstat NE 4, {then}
            LEQON(LEQ1)=YES;
        ELSE
            LEQIIS(LEQ1)=NO;
        ]; {if}
    ]; {loop}
*-----
*Restore original submodel constraints

INCON(III,JJJ)$ (INCON2(III,JJJ) AND NOT(INCOFF(III,JJJ))) = YES;
MANON(III,JJJ)$ (MANON2(III,JJJ) AND NOT(MANOFF(III,JJJ))) = YES;
LLEON(LLE1)$ (NOT(LLEOFF(LLE1))) = YES;
LEQON(LEQ1)$ (NOT(LEQOFF(LEQ1))) = YES;

*-----
*Output results of the deletion filter AND remove IIS from submodel

PUT /@9,'Irreducible inconsistent set (IIS):  '//;

LOOP[(III,JJJ)$INCIIS(III,JJJ),
    FLAG=1;
    PUT @9,'Must fund ',III.TL:4,"01 before "
        I.TE(III):27,III.TL:4,JJJ.TL:2//;
    INCON(III,JJJ)=NO;
    INCOFF(III,JJJ)= YES;
]; {loop}
    IF[FLAG, {then}
        PUT//;
    ]; {if}
    FLAG=0;

LOOP[(III,JJJ)$MANIIS(III,JJJ),
    FLAG=1;
    PUT @9,'Mandated: Must fund ',I.TE(III):27,III.TL:4,JJJ.TL:2//;
    MANON(III,JJJ)=NO;
    MANOFF(III,JJJ)= YES;
]; {loop}
    IF[FLAG, {then}
        PUT//;
    ]; {if}
    FLAG=0;

LOOP[ LLE$LLEIIS(LLE),
    PUT @9,'Fund either but not both: ';
    LOOP[(III,JJJ)$ALE(LLE,III,JJJ),
        PUT @35,I.TE(III):27,III.TL:4,JJJ.TL:2//;
    ]; {loop}
    LLEON(LLE)=NO;
    LLEOFF(LLE)= YES;
    PUT//;

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```

]; {loop}

LOOP[ LEQ$LEQIIS(LEQ),
      PUT @9,'Fund both or neither: ';
      LOOP[(III,JJJ)$AEQ(LEQ,III,JJJ),
            PUT @31,I.TE(III):27,III.TL:4,JJJ.TL:2//;
      ]; {loop}
      LEQON(LEQ)=NO;
      LEQOFF(LEQ)= YES;
      PUT/;
]; {loop}
*-----
*Re-initialize the elastic variable bounds

      INFES.LO(LLE)=0;
      PINFES.LO(LEQ)=0;
      NINFES.LO(LEQ)=0;
      INCINFES.LO(IJ)=0;
      MNINFES.LO(IJ)=0;
      MPINFES.LO(IJ)=0;

      INFES.UP(LLE)=3;
      PINFES.UP(LEQ)=3;
      NINFES.UP(LEQ)=3;
      INCINFES.UP(IJ)=3;
      MNINFES.UP(IJ)=3;
      MPINFES.UP(IJ)=3;

*Remove the identified IIS
      INCIIS(III,JJJ)=NO;
      MANIIS(III,JJJ)=NO;
      LLEIIS(LLE1)=NO;
      LEQIIS(LEQ1)=NO;
*-----
*Re-solve submodel to test for additional IISs

SOLVE LOSER USING MIP MINIMIZING ELASTIC;

]; {loop, IISNUM}
COUNT= 0;
*-----
*Re-initialize the dynamic sets
      INCIIS(III,JJJ)=NO;
      MANIIS(III,JJJ)=NO;
      LLEIIS(LLE1)=NO;
      LEQIIS(LEQ1)=NO;

      INCON(III,JJJ)$INCON2(III,JJJ) = YES;
      MANON(III,JJJ)$MANON2(III,JJJ)= YES;
      LLEON(LLE1)=YES;
      LEQON(LEQ1)=YES;
*-----
]; {if, ELASTICS NE 0}
Z.LO(II,JJ)=0.0;
PUT /;

]; {loop}

IF[NOT(LOGCFLAG), {then}
  PUT @9,'There are no logical infeasibilities in the model.';
]; {if}

```

```

PUTPAGE;
LOST.HDLL= 0;

]; {if logical}

*-----

*Take the elastic variables out of the model prior to executing
*further sensitivity analysis.

INFES.FX(LLE)=0;
PINFES.FX(LEQ)=0;
NINFES.FX(LEQ)=0;
INCINFES.FX(IJ)=0;
MNINFES.FX(IJ)=0;
MPINFES.FX(IJ)=0;

*Re-fix the mandated variables to 1
Z.FX(IJ(I,J))$MANDATE(I,J) =1.0;

*-----

*Un-mandate mandated MDEPs that conflict in the logical constraints

IF[ CONFLICT, {then}

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Analysis of Mandated MDEPs that Conflict with Losers'/
      @5,' _____'///;

PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
      @61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
      @35,' _____',@43,' _____',@49,' _____',@55,' _____'
      @61,' _____',@67,' _____',@73,' _____'//;

PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
      @61,PBAL201,@67,NTURB01,@73,TDEVIATION///;

LOOP[(II,JJ)$MANDCON(II,JJ),
      MANDNUM= MANDNUM +1;
      Z.LO(II,JJ)=0;
      X.LO(II,JJ,T)=0.0;
      SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

      LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

      FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
      FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);
      FOLLOWIN(ii,jj) = no ;

      TNWARVAL = SUM(T,NWARVAL.L(T));
      TNBAL1 = SUM((K,T),NBAL1.L(K,T));
      TNBAL2 = SUM((K,T),NBAL2.L(K,T));
      TPBAL1 = SUM((K,T),PBAL1.L(K,T));
      TPBAL2 = SUM((K,T),PBAL2.L(K,T));
      TNTURB = SUM((I,J,T),NTURB.L(I,J,T));
      TDEVIATION = DEVIATION.L;

PUT MANDNUM:>2:0,'.', 'Un-mandate:  '@28,' MDEP ',@35,'NWARVAL',@43,'NBAL1'
      @49,'NBAL2',@55,'PBAL1'@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
      @28,' _____'@35,' _____',@43,' _____',@49,' _____'

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@55, '_____' @61, '_____', @67, '_____', @73, '_____' /;

PUT I.TE(II):27, II.TL:4, JJ.TL:2, @35, TNWARVAL, @43, TNBAL1
    @49, TNBAL2, @55, TPBAL1, @61, TPBAL2, @67, TNTURB, @73, TDEVIATION//;

LOOP[ (III, JJJ)$FORCEOUT(III, JJJ),
    COUNT= COUNT +1;
    FLAG= 1;

    PUT$(COUNT EQ 1) @60, 'War-value'/@60, '_____' /;
    PUT$(COUNT EQ 1) @5, 'Forced out: ';
    PUT @18, I.TE(III):27, III.TL:4, ' ', JJJ.TL:2, @60, WARVAL(III, JJJ) /;

]; {loop}
COUNT=0;

IF[FLAG, {then}
    PUT/;
]; {if}
FLAG= 0;

LOOP[ (III, JJJ)$FOLLOWIN(III, JJJ),
    COUNT= COUNT + 1;
    FLAG= 1;
    PUT$(COUNT EQ 1) @60, 'War-value'/@60, '_____' /;
    PUT$(COUNT EQ 1) @5, 'Enter: ';
    PUT @18, I.TE(III):27, III.TL:4, ' ', JJJ.TL:2, @60, WARVAL(III, JJJ) /;

]; {loop}
COUNT=0;

IF[FLAG, {then}
    PUT/;
]; {if}
FLAG= 0;

NEWFUND=SUM(X, X.L(II, JJ, T)*ASPIRE(II, JJ, T));
NEWPERC=100*NEWFUND/TOTASPIRE(II, JJ);

IF[NOT(FORCEOUT(II, JJ)),
    PUT/5, 'Funding change for mandate: ';
    PUT @34, I.TE(II):27, II.TL:4, JJ.TL:2//;
    PUT @34, 'Before: ', TOTFUND(II, JJ):<14:0, @54, PERCFUNDA(II, JJ):>6:2, '%'/
        @34, ' After: ', NEWFUND:<14:0, @54, NEWPERC:>6:2, '%'/;
]; {if}

Z.LO(II, JJ)=1.0;
X.LO(II, JJ, T)=1.0;
PUT /;

]; {loop}

LOST.HDLL= 0;
PUTPAGE;

]; {if conflict}
MANDNUM=0;
*-----
*Un-mandate all originally mandated MDEPs one at a time

IF[ ALLMAND, {then}

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```

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Analysis of All Mandated MDEPs '/
      @5,' _____'///;

PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
      @61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
      @35,' _____',@43,' _____',@49,' _____',@55,' _____'
      @61,' _____',@67,' _____',@73,' _____'//;

PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
      @61,PBAL201,@67,NTURB01,@73,DEVIAT01///;

LOOP[(II,JJ)$ (TOTASPIRE(II,JJ) AND (MANDATE(II,JJ) EQ 1)),

      MANDNUM= MANDNUM +1;
      Z.LO(II,JJ)=0;
      X.LO(II,JJ,T)=0.0;
      SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

      LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

      FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
      FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);
      FOLLOWIN(ii,jj) = NO;

      TNWARVAL = SUM(T,NWARVAL.L(T));
      TNBAL1 = SUM((K,T),NBAL1.L(K,T));
      TNBAL2 = SUM((K,T),NBAL2.L(K,T));
      TPBAL1 = SUM((K,T),PBAL1.L(K,T));
      TPBAL2 = SUM((K,T),PBAL2.L(K,T));
      TNTURB = SUM((I,J,T),NTURB.L(I,J,T));
      TDEVIATION = DEVIATION.L;

PUT MANDNUM:>2:0,'.', 'Un-mandate: ' @28,' MDEP ',@35,'NWARVAL',@43,'NBAL1'
      @49,'NBAL2',@55,'PBAL1'@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
      @28,' _____'@35,' _____',@43,' _____',@49,' _____'
      @55,' _____'@61,' _____',@67,' _____',@73,' _____'//;

PUT I.TE(II):27,II.TL:4,JJ.TL:2,@35,TNWARVAL,@43,TNBAL1
      @49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION//;

LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
      COUNT= COUNT +1;
      FLAG= 1;
      PUT$(COUNT EQ 1) @60,'War-value'/@60,' _____'//;
      PUT$(COUNT EQ 1) @5,'Forced out: ';
      PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
      PUT/;
]; {if}
FLAG= 0;

LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
      COUNT= COUNT + 1;
      FLAG= 1;
      PUT$(COUNT EQ 1) @60,'War-value'/@60,' _____'//;
      PUT$(COUNT EQ 1) @5,' Enter: ';

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        PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
    PUT/;
]; {if}
FLAG= 0;

NEWFUND=SUM(T,X.L(II,JJ,T)*ASPIRE(II,JJ,T));
NEWPERC=100*NEWFUND/TOTASPIRE(II,JJ);

IF[NOT(FORCEOUT(II,JJ)),
    PUT/@5,'Funding change for mandate: ';
    PUT @35,I.TE(II):27,II.TL:4,JJ.TL:2/;
    PUT @35,'Before: ',TOTFUND(II,JJ):<14:0,@54,PERCFUNDA(II,JJ):>6:2,'%'/
        @35,' After: ',NEWFUND:<14:0,@54,NEWPERC:>6:2,'%'/;
]; {if}

Z.LO(II,JJ)=1.0;
X.LO(II,JJ,T)=1.0;
PUT /;

]; {loop}

LOST.HDLL= 0;
PUTPAGE;

]; {if allmand}

MANDNUM=0;
*-----
*Un-mandate a group of mandated MDEPs

IF[ GROUPMAN, {then}

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Analysis of a Specified Group of Mandated MDEPs '/
        @5,' _____'///;

PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
        @61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
        @35,'_____',@43,'_____',@49,'_____',@55,'_____'
        @61,'_____',@67,'_____',@73,'_____'//;

PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
        @61,PBAL201,@67,NTURBO1,@73,DEVIATO1///;

LOOP[(II,JJ)$MANGRP(II,JJ),

    Z.LO(II,JJ)=0;
    X.LO(II,JJ,T)=0.0;
]; {loop}

SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);

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```

LOOP[(II,JJ)$MANGRP(II,JJ),
      FOLLOWIN(II,JJ) = NO;
]; {loop}

TNWARVAL = SUM(T,NWARVAL.L(T));
TNBAL1 = SUM((K,T),NBAL1.L(K,T));
TNBAL2 = SUM((K,T),NBAL2.L(K,T));
TPBAL1 = SUM((K,T),PBAL1.L(K,T));
TPBAL2 = SUM((K,T),PBAL2.L(K,T));
TNTURB = SUM((I,J,T),NTURB.L(I,J,T));
TDEVIATION = DEVIATION.L;

PUT 'Group Un-Mandated Result: ',@28,' MDEP ',@35,'NWARVAL'
@43,'NBAL1',@49,'NBAL2',@55,'PBAL1',@61,'PBAL2',@67,'NTURB'
@73,'DEVIATION'/
@28,'_____'@35,'_____',@43,'_____',@49,'_____'
@55,'_____'@61,'_____',@67,'_____',@73,'_____'//;

LOOP[(II,JJ)$MANGRP(II,JJ),
      COUNT = COUNT + 1;
      PUT$(COUNT EQ 1) @35,TNWARVAL,@43,TNBAL1
@49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION//;
      PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;

      PUT COUNT:>2:0,'. ',I.TE(II):27,II.TL:4,JJ.TL:2,@60,WARVAL(II,JJ);
      PUT/;
]; {loop}
COUNT = 0;
PUT/;

LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
      COUNT= COUNT +1;
      FLAG= 1;
      PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
      PUT$(COUNT EQ 1) @5,'Forced out: ';
      PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
      PUT/;
]; {if}
FLAG= 0;

LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
      COUNT= COUNT + 1;
      FLAG= 1;
      PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
      PUT$(COUNT EQ 1) @5,'Enter: ';
      PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
      PUT/;
]; {if}
FLAG= 0;

LOOP[(II,JJ)$MANGRP(II,JJ),

      NEWFUND=SUM(T,X.L(II,JJ,T)*ASPIRE(II,JJ,T));

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NEWPERC=100*NEWFUND/TOTASPIRE(II,JJ);

IF[NOT(FORCEOUT(II,JJ)),
  PUT/@5,'Funding change for mandate: ';
  PUT @35,I.TE(II):27,II.TL:4,JJ.TL:2/;
  PUT @35,'Before: ',TOTFUND(II,JJ):<14:0,@54,PERCFUNDA(II,JJ):>6:2,'%'/
    @35,' After: ',NEWFUND:<14:0,@54,NEWPERC:>6:2,'%'/;
]; {if}
]; {loop}

LOOP[(II,JJ)$MANGRP(II,JJ),
  Z.LO(II,JJ)=1.0;
  X.LO(II,JJ,T)=1.0;
]; {loop}

LOST.HDLL= 0;
PUTPAGE;

]; {if groupman}

MANDNUM=0;
*-----
*Summary report of the Losers

IF[GROUPMAN, {then}

  PUTHD '#',TESTNUM:<2:0,' Summary of Losers'/
    @5,' '///;

  PUTHD 'MDEP TITLE',@28,'MDEP/INC',@38,'TOT-ASPIRED',@51,'WAR-VALUE'/;
  PUTHD ' ',@28,' ',@38,' ',@51,' '/;

  LOOP[IJ(II,JJ)$(Z.L(II,JJ) EQ 0),
    PUT @1,I.TE(II),@28,II.TL:4,JJ.TL:<2:0,@38,TOTASPIRE(II,JJ):<10:0
      @51,WARVAL(II,JJ):<5:2/;
  ]; {loop}

  PUTPAGE;
  LOST.HDLL=0;
  ]; {if groupman}
*-----
*Force the feasible MDEPs into the solution one at a time

IF[ FEASIBL, {then}

  TESTNUM= TESTNUM +1;
  PUTHD '#',TESTNUM:<2:0,' Analysis of Feasible Losers '/
    @5,' '///;

  PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
    @61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
    @35,' ',@43,' ',@49,' ',@55,' '
    @61,' ',@67,' ',@73,' '/;

  PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
    @61,PBAL201,@67,NTURBO1,@73,DEVIATO1///;

  LOOP[(II,JJ)$FEASIBLE(II,JJ),
    FEASNUM= FEASNUM + 1;
    Z.FX(II,JJ)=1.0;
    SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

```

```

IF[RDA3.modelstat NE 4, {then}

  LOS1(IJ)=YESS(Z.L(IJ) EQ 0);

  FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
  FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);
  FOLLOWIN(II,JJ) = NO;

  TNWARVAL = SUM(T,NWARVAL.L(T));
  TNBAL1 = SUM((K,T),NBAL1.L(K,T));
  TNBAL2 = SUM((K,T),NBAL2.L(K,T));
  TPBAL1 = SUM((K,T),PBAL1.L(K,T));
  TPBAL2 = SUM((K,T),PBAL2.L(K,T));
  TNTURB = SUM((I,J,T),NTURB.L(I,J,T));
  TDEVIATION = DEVIATION.L;
PUT/;
PUT FEASNUM:>2:0,'.', 'Force-in: '@28,' MDEP ',@35,'NWARVAL',@43,'NBAL1'
@49,'NBAL2',@55,'PBAL1',@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
@28,'_____'@35,'_____'@43,'_____'@49,'_____'
@55,'_____'@61,'_____'@67,'_____'@73,'_____'//;

  PUT I.TE(II):<28:0,II.TL:4,JJ.TL:2,@35,TNWARVAL,@43,TNBAL1
    @49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION//;

LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
  COUNT= COUNT +1;
  FLAG= 1;
  PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
  PUT$(COUNT EQ 1) @5,'Forced out: ';
  PUT @18,I.TE(III):<28:0,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

  IF[FLAG, {then}
    PUT/;
  ]; {if}
  FLAG= 0;

LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
  COUNT= COUNT + 1;
  FLAG= 1;
  PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
  PUT$(COUNT EQ 1) @4,'Followed-in: ';
  PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

  IF[FLAG, {then}
    PUT/;
  ]; {if}
  FLAG= 0;

ELSE
  FEASIBLE(II,JJ)=NO;
  INFASIBLE(II,JJ)=YES;
]; {if}

Z.LO(II,JJ)=0.0;
PUT /;

```

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]; {loop}

LOST.HDLL= 0;
PUTPAGE;

]; {if feasibl}

FEASNUM=0;
*-----
*Force in a group of feasible MDEPs into the solution at the same time

IF[ GROUPFES, {then}

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Analysis of a Specified Group of Feasible Losers '/'
@5,'_____''//';

PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
@35,'_____',@43,'_____',@49,'_____',@55,'_____'
@61,'_____',@67,'_____',@73,'_____'//;

PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
@61,PBAL201,@67,NTURB01,@73,DEVIAT01//;

LOOP[(II,JJ)$FEASGRP(II,JJ),
Z.FX(II,JJ)=1.0;
]; {loop}

SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

IF[RDA3.modelstat NE 4, {then}

LOOP[(II,JJ)$FEASGRP(II,JJ),
FEASIBLE(II,JJ)= YES;
]; {loop}

LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);

LOOP[(II,JJ)$FEASGRP(II,JJ),
FOLLOWIN(II,JJ) = NO;
]; {loop}

TNWARVAL = SUM(T,NWARVAL.L(T));
TNBAL1 = SUM((K,T),NBAL1.L(K,T));
TNBAL2 = SUM((K,T),NBAL2.L(K,T));
TPBAL1 = SUM((K,T),PBAL1.L(K,T));
TPBAL2 = SUM((K,T),PBAL2.L(K,T));
TNTURB = SUM((I,J,T),NTURB.L(I,J,T));
TDEVIATION = DEVIATION.L;

PUT 'Group Force-in Result: '@28,' MDEP '@35,'NWARVAL'
@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'@61,'PBAL2',@67,'NTURB'
@73,'DEVIATION'/
@28,'_____'@35,'_____',@43,'_____',@49,'_____'
@55,'_____'@61,'_____',@67,'_____',@73,'_____'//;

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LOOP[(II,JJ)$FEASGRP(II,JJ),
  COUNT = COUNT + 1;
  PUT$(COUNT EQ 1) @35,TNWARVAL,@43,TNBAL1
    @49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION//;
  PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____ '/;
  PUT COUNT:>3:0,'. ',I.TE(II):27,II.TL:4,JJ.TL:2,@60,WARVAL(II,JJ);
  PUT/;
]; {loop}
COUNT = 0;
PUT/;

LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
  COUNT= COUNT +1;
  FLAG= 1;
  PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____ '/;
  PUT$(COUNT EQ 1) @5,'Forced out: ';
  PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
  PUT/;
]; {if}
FLAG= 0;

LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
  COUNT= COUNT + 1;
  FLAG= 1;
  PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____ '/;
  PUT$(COUNT EQ 1) @4,'Followed-in: ';
  PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
  PUT/;
]; {if}
FLAG= 0;

ELSE
  LOOP[(II,JJ)$FEASGRP(II,JJ),
    FEASIBLE(II,JJ)=NO;
    INFESIBLE(II,JJ)=YES;
  ]; {loop}
]; {if}

LOOP[(II,JJ)$FEASGRP(II,JJ),
  Z.LO(II,JJ)=0.0;
]; {loop}

PUT /;

LOST.HDLL= 0;
PUTPAGE;

]; {if groupfes}

FEASNUM=0;
*-----
*Summary report of the Losers

```

```

IF[GROUPFES, {then}

  PUTHD '#',TESTNUM:<2:0,' Summary of Losers'/
    @5,'_____'////;

  PUTHD 'MDEP TITLE',@28,'MDEP/INC',@38,'TOT-ASPIRED',@51,'WAR-VALUE'/;
  PUTHD '_____',@28,'_____',@38,'_____',@51,'_____'//;

  LOOP[IJ(II,JJ)$(Z.L(II,JJ) EQ 0),
    PUT @1,I.TE(II),@28,II.TL:4,JJ.TL:<2:0,@38,TOTASPIRE(II,JJ):<10:0
    @51,WARVAL(II,JJ):<5:2//;
  ]; {loop}

  PUTPAGE;
  LOST.HDLL=0;
  ]; {if groupfes}

*-----

*Budget analysis, BEFORE decision

IF[BUDGETB, {then}

OPTION Integer2 = 0;

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Budget Analysis Before Decision '/
  @5,'_____'////;

  PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
    @61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
    @35,'_____',@43,'_____',@49,'_____',@55,'_____'
    @61,'_____',@67,'_____',@73,'_____'//;

  PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
    @61,PBAL201,@67,NTURBO1,@73,DEVIATO1///;

  BUDGET(T)$ALTBUDGET(T) = ALTBUDGET(T);

  SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

  IF[RDA3.modelstat NE 4, {then}

*New parameter values

NTOTFUN(IJ)      = SUM( t, X.L(IJ,t) * ASPIRE(IJ,t) ) ;
NMISNFUN(k,t)    = SUM( IJ $ MSNAREA(IJ,k), X.L(IJ,t) *
  ASPIRE(IJ,t) ) ;
NTOTYEAFF(t)     = SUM( k, NMISNFUN(k,t) ) ;
NTOTYEAFA(t)     = SUM( IJ, ASPIRE(IJ,t) ) ;
NTOTMISF(k)      = SUM( t, NMISNFUN(k,t) ) ;
NTOTMISA(k)      = SUM( IJ $ MSNAREA(IJ,k), TOTASPIRE(IJ) ) ;
NTOTAS           = SUM( k, NTOTMISA(k) ) ;
NTOTSPEN         = SUM( k, NTOTMISF(k) ) ;
NTOTBUDGE        = SUM( t, BUDGET(t) ) ;
NFUNDPER(IJ,T)   = X.L(IJ,T) * 100.0 ;
NFUNDMONE(IJ,T)  = NFUNDPER(IJ,T) * ASPIRE(IJ,T)/100;

NPERCFUNA(IJ(I,J)) = 100*NTOTFUN(I,J)/TOTASPIRE(I,J);
NPCTFUNM(K)        = (100*NTOTMISF(k)/NTOTMISA(k))$(NTOTMISA(K) NE 0);
NPCTBUDGEM(K)      = 100*NTOTMISF(k)/NTOTBUDGE;

```

```

NPCTALLOM(K)      = 100*NTOTMISF(K)/NTOTSPEN;
NOVERALPCA        = (100*NTOTSPEN/NTOTAS)$ (NTOTAS NE 0);
NOVERALPCB        = 100*NTOTSPEN/NTOTBUDGE;
NPCTUNSPB        = 100-NOVERALPCB;
NSUMASPIR        = SUM(IJ,TOTASPIRE(IJ));
NSUMFUN          = SUM(IJ,NTOTFUN(IJ));
NPCTFUNA         = 100*SUM(IJ,NTOTFUN(IJ))/SUM(IJ,TOTASPIRE(IJ));
NSUMFUNW         = SUM(IJ$NTOTFUN(IJ),WARVAL(IJ));
NSUMFUNO         = SUM(IJ$NTOTFUN(IJ),OSCOST(IJ));
NEXCASPIR        = SUM(EXC,TOTASPIRE(EXC));
NEXCNU           = CARD(EXC);
NEXCWARVA        = SUM(EXC,WARVAL(EXC));

  LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

  FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
  FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);

  TNWARVAL = SUM(T,NWARVAL.L(T));
  TNBAL1 = SUM((K,T),NBAL1.L(K,T));
  TNBAL2 = SUM((K,T),NBAL2.L(K,T));
  TPBAL1 = SUM((K,T),PBAL1.L(K,T));
  TPBAL2 = SUM((K,T),PBAL2.L(K,T));
  TNTURB = SUM((I,J,T),NTURB.L(I,J,T));
  TDEVIATION = DEVIATION.L;

  PUT @35,'NWARVAL',@43,'NBAL1'
    @49,'NBAL2',@55,'PBAL1'@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
    @35,'_____',@43,'_____',@49,'_____'
    @55,'_____'@61,'_____',@67,'_____',@73,'_____'//;

  PUT 'New results: ',@35,TNWARVAL,@43,TNBAL1
    @49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION///;

  PUT @5,'Budget profile: ';
  LOOP[T,PUT @24,T.TL:<5:0,ALTBUDGET(T):<20:0/;
]; {loop}
  PUT///;

  LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
    COUNT= COUNT +1;
    FLAG= 1;
    PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
    PUT$(COUNT EQ 1) @5,'Forced out: ';
    PUT @18,1.TE(III):<28:0,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
  COUNT=0;

  IF[FLAG, {then}
    PUT/;
  ]; {if}
  FLAG= 0;

  LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
    COUNT= COUNT + 1;
    FLAG= 1;
    PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
    PUT$(COUNT EQ 1) @5,'Enter: ';
    PUT @18,1.TE(III):<28:0,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
  COUNT=0;

```



```

        IF[FLAG, {then}
            PUT/;
        ]; {if}
        FLAG= 0;
        LOST.HDLL=0;
        PUTPAGE;
        PUTHD ///
        'MDEP TITLE',@28,'MDEP/INC',@46,'TOTASPIRED'
        @57,'TOTFUND',@66,'PCT-FUNDED'/

        '_____',@28,'_____',@46,'_____',@57,'_____'
        @66,'_____'//;

        LOOP(IJ(I,J),
            PUT$(TOTFUND(I,J)) @1,I.TE(I):<28:0,@28,I.TL:4,J.TL:<2:0,@35,'old--> '
                @46,TOTASPIRE(I,J):<10:0,@57,TOTFUND(I,J):<10:0
                @66,PERCFUNDA(I,J):<6:2//;
            PUT$FOLLOWIN(I,J) @1,I.TE(I):<28:0,@28,I.TL:4,J.TL:<2:0,@35,'old--> '
                @46,'-Not funded-'/;

            PUT @35,'new--> '
            PUT$(NTOTFUN(I,J)) @46,TOTASPIRE(I,J):<10:0,@57,NTOTFUN(I,J):<10:0
                @66,NPERCFUNA(I,J):<6:2//;
            PUT$FORCEOUT(I,J) @46,'-Not funded-'/;

        );
        PUT '_____'
            '_____'//;
        PUT 'TOTALS:',@9,'old--> ',@18,'% of Budget: ',OVERALPCTB:<6:2
            @46,SUMASPIRE:<9:2,@56,SUMFUND:<9:2,@66,PCTFUNDA:<6:2//;
        PUT @9,'new--> ',@18,'% of Budget: ',NOVERALPCB:<6:2
            @46,NSUMASPIR:<9:2,@56,NSUMFUN:<9:2,@66,NPCTFUNA:<6:2//;

        ELSE PUT @5,'Infeasible budget level'/;
    ]; {if}

    LOST.HDLL= 0;
    PUTPAGE;

]; {if budgetb}
*-----
*Summary report of the Losers

IF[BUDGETB, {then}

    PUTHD '#',TESTNUM:<2:0,' Summary of Losers'/
        @5,'_____'////;

    PUTHD 'MDEP TITLE',@28,'MDEP/INC',@38,'TOT-ASPIRED',@51,'WAR-VALUE'/;
    PUTHD '_____',@28,'_____',@38,'_____',@51,'_____'//;

    LOOP[IJ(II,JJ)$(Z.L(II,JJ) EQ 0),
        PUT @1,I.TE(II),@28,II.TL:4,JJ.TL:<2:0,@38,TOTASPIRE(II,JJ):<10:0
            @51,WARVAL(II,JJ):<5:2//;

    ]; {loop}

    PUTPAGE;
    LOST.HDLL=0;
]; {if budgetb}

```

```

*-----
*Formulation of a model that encourages old variable values to remain the same

FREE VARIABLE DEVIAT2 The original RDA3 objective function plus the sum
*           of the weighted persistence deviations;

POSITIVE VARIABLES
    ZPOS(I,J)    Accounts for positive deviation in Z variables
    ZNEG(I,J)    Accounts for negative deviation in Z variables;

SCALARS
    WPOS    Penalty for positive deviation in Z variables
    WNEG    Penalty for negative deviation in Z variables
    ALPHA   Level of persistence;

*Variable bounds
    ZPOS.LO(IJ)=0;
    ZPOS.UP(IJ)=1.0;
    ZNEG.LO(IJ)=0;
    ZNEG.UP(IJ)=1.0;

*Set weights and level of persistence
    WPOS=1;
    WNEG=20;
    ALPHA=.9;

* formulation of objective

EQUATIONS
    VARPERSIS(I,J) Variable persistence equation
    OBJDEF2 Objective function;

VARPERSIS(IJ(I,J))..Z(I,J)=E= Z01(I,J)+ZPOS(I,J)-ZNEG(I,J);

OBJDEF2..      (1-ALPHA)*( SUM(t, WEIGHT1(t) * NWARVAL(t))
                  + SUM((k,t), WEIGHT2(t) * NBAL1(k,t))
                  + SUM((k,t), WEIGHT3(t) * NBAL2(k,t))
                  + SUM((k,t), WEIGHT2(t) * PBAL1(k,t))
                  + SUM((k,t), WEIGHT3(t) * PBAL2(k,t))
                  + SUM((IJ,t) $ (ASPIRE(IJ,t) * ASPIRE(IJ,t-1)),
                      WEIGHT4(t) * NTURB(IJ,t)) / SCALTURB)
                  +SUM(IJ,ALPHA*WPOS*ZPOS(IJ))
                  +SUM(IJ,ALPHA*WNEG*ZNEG(IJ))
                  =E= DEVIAT2 ;

    MODEL PERSIST/WARVALUE,BALANCE,TURBULENCE,MODCOST,SUSTAIN
    LINKAGE,FRACFUND,INCREMENT,{YRMIN,}LOGCLE,LOGCEQ
    OBJDEF2,VARPERSIS/;

*-----
*Budget analysis, AFTER decision is made AND using persistence to
*encourage original projects to stay in the solution

IF[BUDGETA, {then}

OPTION INTEGER2 = 0;

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Budget Analysis After Decision (with persistence)'/
@5,'_____';

```

```

PUTHD @35, 'NWARVAL', @43, 'NBAL1', @49, 'NBAL2', @55, 'PBAL1'
    @61, 'PBAL2', @67, 'NTURB', @73, 'DEVIATION' /
    @35, '_____', @43, '_____', @49, '_____', @55, '_____'
    @61, '_____', @67, '_____', @73, '_____' /;

PUTHD 'RDA3 RESULTS', @35, NWARVAL01, @43, NBAL101, @49, NBAL201, @55, PBAL101
    @61, PBAL201, @67, NTURB01, @73, DEVIAT01 ///;

BUDGET(T)$ALTBUDGET(T) = ALTBUDGET(T);

SOLVE PERSIST MINIMIZING DEVIAT2 USING MIP;

IF[PERSIST.modelstat NE 4, {then}

*New parameter values

NTOTFUN(IJ)      = SUM( t, X.L(IJ,t) * ASPIRE(IJ,t) ) ;
NMISNFUN(k,t)    = SUM( IJ $ MSNAREA(IJ,k), X.L(IJ,t) *
    ASPIRE(IJ,t) ) ;
NTOTYEAFF(t)     = SUM( k, NMISNFUN(k,t) ) ;
NTOTYEAFF(t)     = SUM( IJ, ASPIRE(IJ,t) ) ;
NTOTMISF(k)      = SUM( t, NMISNFUN(k,t) ) ;
NTOTMISA(k)      = SUM( IJ $ MSNAREA(IJ,k), TOTASPIRE(IJ) ) ;
NTOTAS           = SUM( k, NTOTMISA(k) ) ;
NTOTSPEN         = SUM( k, NTOTMISF(k) ) ;
NTOTBUDGE        = SUM( t, BUDGET(t) ) ;
NFUNDPER(IJ,T)   = X.L(IJ,T) * 100.0 ;
NFUNDMONE(IJ,T)  = NFUNDPER(IJ,T) * ASPIRE(IJ,T)/100;

NPERCFUNA(IJ(I,J)) = 100*NTOTFUN(I,J)/TOTASPIRE(I,J);
NPCTFUNM(K)        = (100*NTOTMISF(k)/NTOTMISA(k))$(NTOTMISA(K) NE 0);
NPCTBUDGEM(K)      = 100*NTOTMISF(k)/NTOTBUDGE;
NPCTALLOM(K)       = 100*NTOTMISF(k)/NTOTSPEN;
NOVERALPCA         = (100*NTOTSPEN/NTOTAS)$(NTOTAS NE 0);
NOVERALPCB         = 100*NTOTSPEN/NTOTBUDGE;
NPCTUNSPER         = 100-NOVERALPCB;
NSUMASPIR          = SUM(IJ, TOTASPIRE(IJ));
NSUMFUN            = SUM(IJ, NTOTFUN(IJ));
NPCTFUNA           = 100*SUM(IJ, NTOTFUN(IJ))/SUM(IJ, TOTASPIRE(IJ));
NSUMFUNW           = SUM(IJ$NTOTFUN(IJ), WARVAL(IJ));
NSUMFUNO           = SUM(IJ$NTOTFUN(IJ), OSCOST(IJ));
NEXCASPIR          = SUM(EXC, TOTASPIRE(EXC));
NEXCNU             = CARD(EXC);
NEXCWARVA          = SUM(EXC, WARVAL(EXC));

LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);

TNWARVAL = SUM(T, NWARVAL.L(T));
TNBAL1 = SUM((K,T), NBAL1.L(K,T));
TNBAL2 = SUM((K,T), NBAL2.L(K,T));
TPBAL1 = SUM((K,T), PBAL1.L(K,T));
TPBAL2 = SUM((K,T), PBAL2.L(K,T));
TNTURB = SUM((I,J,T), NTURB.L(I,J,T));

TDEVIATION = (DEVIAT2.L-SUM(IJ, ALPHA*WPOS*ZPOS.L(IJ))
    -SUM(IJ, ALPHA*WNEG*ZNEG.L(IJ)))/(1-ALPHA) ;

```

```

PUT @35,'NWARVAL',@43,'NBAL1'
@49,'NBAL2',@55,'PBAL1'@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
@35,'_____',@43,'_____',@49,'_____'
@55,'_____'@61,'_____',@67,'_____',@73,'_____'//;

PUT 'New results: ',@35,TNWARVAL,@43,TNBAL1
@49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION///;

PUT @5,'Budget profile: ';
LOOP[T,PUT @24,T.TL:<5:0,ALTBUDGET(T):<20:0/;
]; {loop}
PUT///;

LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
COUNT= COUNT +1;
FLAG= 1;
PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
PUT$(COUNT EQ 1) @5,'Forced out: ';
PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
PUT/;
]; {if}
FLAG= 0;

LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
COUNT= COUNT + 1;
FLAG= 1;
PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
PUT$(COUNT EQ 1) @5,'Enter: ';
PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
PUT/;
]; {if}
FLAG= 0;
LOST.HDLL=0;
PUTPAGE;
PUTHD ///
'MDEP TITLE',@28,'MDEP/INC',@46,'TOTASPIRED'
@57,'TOTFUND',@66,'PCT-FUNDED' /

'_____',@28,'_____',@46,'_____',@57,'_____'
@66,'_____'//;

LOOP(IJ(I,J),
PUT$(TOTFUND(I,J)) @1,I.TE(I):<28:0,@28,I.TL:4,J.TL:<2:0,@35,'old--> ',@46
TOTASPIRE(I,J):<10:0,@57,TOTFUND(I,J):<10:0
@66,PERCFUNDA(I,J):<6:2//;
PUT$FOLLOWIN(I,J) @1,I.TE(I):<28:0,@28,I.TL:4,J.TL:<2:0,@35,'old--> '@46
'-Not funded-'/;

PUT @35,'new--> '
PUT$(NTOTFUN(I,J)) @46,TOTASPIRE(I,J):<10:0,@57,NTOTFUN(I,J):<10:0
@66,NPERCFUNA(I,J):<6:2//;
PUT$FORCEOUT(I,J) @46,'-Not funded-'/;

```

```

);
PUT ' _____ '
    ' _____ ';;

PUT 'TOTALS:',@9,'old--> ',@18,'% of Budget: ',OVERALPCTB:<6:2
    @46,SUMASPIRE:<9:2,@56,SUMFUND:<9:2,@66,PCTFUNDA:<6:2/;
PUT @9,'new--> ',@18,'% of Budget: ',NOVERALPCB:<6:2
    @46,NSUMASPIR:<9:2,@56,NSUMFUN:<9:2,@66,NPCTFUNA:<6:2/;

ELSE PUT @5,'Infeasible budget level'/;
]; {if}

LOST.HDLL= 0;
PUTPAGE;

]; {if budgeta}
*-----
*Summary report of the Losers

IF[BUDGETA, {then}

    PUTHD '#',TESTNUM:<2:0,' Summary of Losers'/
        @5,' _____ '///;

    PUTHD 'MDEP TITLE',@28,'MDEP/INC',@38,'TOT-ASPIRED',@51,'WAR-VALUE'/;
    PUTHD ' _____ ',@28,' _____ ',@38,' _____ ',@51,' _____ '/;

    LOOP[IJ(II,JJ)$ (Z.1.(II,JJ) EQ 0),
        PUT @1,I.TE(II),@28,II.TL:4,JJ.TL:<2:0,@38,TOTASPIRE(II,JJ):<10:0
            @51,WARVAL(II,JJ):<5:2/;
    ]; {loop}

    PUTPAGE;
    LOST.HDLL=0;
    ]; {if budgeta}

*-----
*Budget analysis, AFTER decision is made AND fixing the original solution

IF[BUDGETA2, {then}

    OPTION INTEGER2 = 0;

    TESTNUM= TESTNUM +1;
    PUTHD '#',TESTNUM:<2:0,' Budget Analysis After Decision (old solution fixed)'/
        @5,' _____ '///;

        LOOP[IJ(I,J)$ (Z01(I,J) EQ 1),
            Z.FX(I,J)=1.0;
        ]; {loop}

        BUDGET(T)$ALTBUDGET(T) = ALTBUDGET(T);
        TOTBUDGET= SUM(T$ALTBUDGET(T), ALTBUDGET(T));

*-----
*Check to see if a loser MDEP breaks the budget in any given year for
*either a 100% funding policy or a partial funding policy of mandated
*projects.

MANDCOST(T) = SUM((II,JJ) $ MANDATE(II,JJ),
    ASPIRE(II,JJ,T) * (1$FULL+MINLEVYR(II,JJ)$ (FULL EQ 0))) ;

```

```

MANDOSCOST = SUM( (II,JJ) $ MANDATE(II,JJ),
                  OSCOST(II,JJ) * (1$FULL+MINLEVYR(II,JJ)$ (FULL EQ 0))) ;

MANCOST = SUM((II,JJ)$MANDATE(II,JJ),
              TOTASPIRE(II,JJ)*(1$FULL+MINLEVEL(II,JJ)$ (FULL EQ 0)));

TESTNUM=TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Budget and OSCOST Feasibility Analysis (for budget
analysis)'/
@5,'_____';

PUT @5,'Budget profile: ';
LOOP[T,PUT @24,T.TL:<5:0,BUDGET(T):<20:0//;
]; {loop}
PUT/@5,'Maximum total OSCOST: ',@29,MAXOSCOST:<20:0//;

PUT @5,'Result: ';

LOOP[T,
      {if true then violates the annual budget constraint}
      IF[ SUM((I,J)$ (Z01(I,J) AND NOT(MANDATE(I,J))),
            ASPIRE(I,J,T)*MINLEVYR(I,J)) +MANDCOST(T)
            GT BUDGET(T),
      {then}
        COUNT= COUNT + 1;
        BUDGTNUM$(COUNT EQ 1)= BUDGTNUM +1;

        PUT$(COUNT EQ 1) @14,BUDGTNUM:>2:0,'.';
        PUT$(COUNT EQ 1) @18,'Violates the budget constraint in year: ';
        PUT @60,T.TL//;

        FEASIBLE(I,J)=NO;
        INFEASIBLE(I,J)=YES;
      ]; {if}
]; {loop}

IF[COUNT NE 0,
{then}
  PUT//;
]; {if}

IF[
  SUM((I,J)$ (Z01(I,J) AND NOT(MANDATE(I,J))),
      MINLEVEL(I,J)*TOTASPIRE(I,J)) + MANCOST
      GT TOTBUDGET,
{then}
  COUNT= COUNT + 1;
  BUDGTNUM$(COUNT EQ 1)= BUDGTNUM +1;

  PUT$(COUNT EQ 1) @14,BUDGTNUM:>2:0,'.';
  PUT$(COUNT EQ 1) @18,'Violates the total budget constraint ';

  FEASIBLE(I,J)=NO;
  INFEASIBLE(I,J)=YES;
]; {if}

IF[COUNT NE 0,
{then}
  PUT//;
]; {if}

*-----
*check adherence to maximum OSCOST

```

```

        {if true then does not adhere to the maximum OSCOST}
IF[SUM((I,J)$ (ZO1(I,J) AND NOT(MANDATE(I,J))),
        OSCOST(I,J) * MINLEVYR(I,J)) + MANDOSCOST
        GT MAXOSCOST,
{then}
    BUDGTNUM$(COUNT EQ 0)= BUDGTNUM +1;
    PUT$(COUNT EQ 0) @14,BUDGTNUM:>2:0,','
    PUT$(COUNT EQ 0)
    PUT @18,'Does not adhere to the maximum operation and support costs.'//;

    FEASIBLE(I,J)=NO;
    INFEASIBLE(I,J)=YES;
}; {if}
COUNT=0;

LOOP[(I,J)$INFEASIBLE(I,J),
    COUNT=COUNT+1;
]; {loop}
IF[COUNT EQ 0, PUT @14,'The original solution is budget and OSCOST feasible'//;
]; {if}

BUDGTNUM= 0; {re-initialize counter}
COUNT= 0; {re-initialize counter}
PUTPAGE;
LOST.HDLL= 0;
*-----

PUTHD @35,'NWARVAL',@43,'NBAL1',@49,'NBAL2',@55,'PBAL1'
    @61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
    @35,'_____',@43,'_____',@49,'_____',@55,'_____'
    @61,'_____',@67,'_____',@73,'_____'//;

PUTHD 'RDA3 RESULTS',@35,NWARVAL01,@43,NBAL101,@49,NBAL201,@55,PBAL101
    @61,PBAL201,@67,NTURB01,@73,DEVIAT01///;

SOLVE RDA3 MINIMIZING DEVIATION USING MIP;

IF[RDA3.modelstat NE 4, {then}

*New parameter values

NTOTFUN(IJ)      = SUM( t, X.L(IJ,t) * ASPIRE(IJ,t) ) ;
NMISNFUN(k,t)    = SUM( IJ $ MSNAREA(IJ,k), X.L(IJ,t) *
                        ASPIRE(IJ,t) ) ;
NTOTYEAFF(t)     = SUM( k, NMISNFUN(k,t) ) ;
NTOTYEAFA(t)     = SUM( IJ, ASPIRE(IJ,t) ) ;
NTOTMISF(k)      = SUM( t, NMISNFUN(k,t) ) ;
NTOTMISA(k)      = SUM( IJ $ MSNAREA(IJ,k), TOTASPIRE(IJ) ) ;
NTOTAS           = SUM( k, NTOTMISA(k) ) ;
NTOTSPEN         = SUM( k, NTOTMISF(k) ) ;
NTOTBUDGE        = SUM( t, BUDGET(t) ) ;
NFUNDPER(IJ,T)   = X.L(IJ,T) * 100.0 ;
NFUNDMONE(IJ,T)  = NFUNDPER(IJ,T) * ASPIRE(IJ,T)/100;

NPERCFUNA(IJ(I,J)) = 100*NTOTFUN(I,J)/TOTASPIRE(I,J);
NPCTFUNM(K)        = (100*NTOTMISF(k)/NTOTMISA(k))$(NTOTMISA(K) NE 0);
NPCTBUDGEM(K)      = 100*NTOTMISF(k)/NTOTBUDGE;
NPCTALLOM(K)       = 100*NTOTMISF(k)/NTOTSPEN;
NOVERALPCA         = (100*NTOTSPEN/NTOTAS)$(NTOTAS NE 0);
NOVERALPCB         = 100*NTOTSPEN/NTOTBUDGE;

```

```

NPCTUNSPB      = 100-NOVERALPCB;
NSUMASPIR      = SUM(IJ,TOTASPIRE(IJ));
NSUMFUN        = SUM(IJ,NTOTFUN(IJ));
NPCTFUNA       = 100*SUM(IJ,NTOTFUN(IJ))/SUM(IJ,TOTASPIRE(IJ));
NSUMFUNW       = SUM(IJ$NTOTFUN(IJ),WARVAL(IJ));
NSUMFUNO       = SUM(IJ$NTOTFUN(IJ),OSCOST(IJ));
NEXCASPIR      = SUM(EXC,TOTASPIRE(EXC));
NEXCNU         = CARD(EXC);
NEXCWARVA      = SUM(EXC,WARVAL(EXC));

LOS1(IJ)=YES$(Z.L(IJ) EQ 0);

FORCEOUT(IJ)=LOS1(IJ)- LOS(IJ);
FOLLOWIN(IJ)=LOS(IJ)-LOS1(IJ);

TNWARVAL = SUM(T,NWARVAL.L(T));
TNBAL1 = SUM((K,T),NBAL1.L(K,T));
TNBAL2 = SUM((K,T),NBAL2.L(K,T));
TPBAL1 = SUM((K,T),PBAL1.L(K,T));
TPBAL2 = SUM((K,T),PBAL2.L(K,T));
TNTURB = SUM((I,J,T),NTURB.L(I,J,T));

TDEVIATION = DEVIATION.L;

PUT @35,'NWARVAL',@43,'NBAL1'
@49,'NBAL2',@55,'PBAL1'@61,'PBAL2',@67,'NTURB',@73,'DEVIATION'/
@35,'_____',@43,'_____',@49,'_____'
@55,'_____'@61,'_____'@67,'_____'@73,'_____'//;

PUT 'New results: ',@35,TNWARVAL,@43,TNBAL1
@49,TNBAL2,@55,TPBAL1,@61,TPBAL2,@67,TNTURB,@73,TDEVIATION///;

$ONTEXT
PUT @5,'Budget profile: ';
LOOP[T,PUT @24,T.TL:<5:0,ALTBUDGET(T):<20:0/;
]; {loop}
PUT///;

$OFFTEXT
LOOP[(III,JJJ)$FORCEOUT(III,JJJ),
COUNT= COUNT +1;
FLAG= 1;
PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
PUT$(COUNT EQ 1) @5,'Forced out: ';
PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}
PUT/;
]; {if}
FLAG= 0;

LOOP[(III,JJJ)$FOLLOWIN(III,JJJ),
COUNT= COUNT + 1;
FLAG= 1;
PUT$(COUNT EQ 1) @60,'War-value'/@60,'_____'//;
PUT$(COUNT EQ 1) @5,'Enter: ';
PUT @18,I.TE(III):27,III.TL:4,' ',JJJ.TL:2,@60,WARVAL(III,JJJ)/;
]; {loop}
COUNT=0;

IF[FLAG, {then}

```



```

        PUT/;
    ]; {if}
        FLAG= 0;
        LOST.HDLL=0;
        PUTPAGE;
        PUTHD ///
        'MDEP TITLE',@28,'MDEP/INC',@46,'TOTASPIRED'
        @57,'TOTFUND',@66,'PCT-FUNDED'/

        '_____',@28,'_____',@46,'_____',@57,'_____'
        @66,'_____'//;

    LOOP(IJ(I,J),
        PUT$(TOTFUND(I,J)) @1,I.TE(I):<27,@28,I.TL:4,J.TL:<2:0,@35,'old--> ',@46
        TOTASPIRE(I,J):<10:0,@57,TOTFUND(I,J):<10:0
        @66,PERCFUNDA(I,J):<6:2//;
        PUT$FOLLOWIN(I,J) @1,I.TE(I):<29,@28,I.TL:4,J.TL:<2:0,@35,'old--> '@46
        '-Not funded-'//;

        PUT @35,'new--> '
        PUT$(NTOTFUN(I,J)) @46,TOTASPIRE(I,J):<10:0,@57,NTOTFUN(I,J):<10:0
        @66,NPERCFUNDA(I,J):<6:2//;
        PUT$FORCEOUT(I,J) @46,'-Not funded-'//;

    );
    PUT '_____'
    '_____'//;

    PUT 'TOTALS:',@9,'old--> ',@18,'% of Budget: ',OVERALPCTB:<6:2
    @46,SUMASPIRE:<9:2,@56,SUMFUND:<9:2,@66,PCTFUNDA:<6:2//;
    PUT @9,'new--> ',@18,'% of Budget: ',NOVERALPCB:<6:2
    @46,NSUMASPIR:<9:2,@56,NSUMFUN:<9:2,@66,NPCTFUNA:<6:2//;

    LOOP[IJ(I,J)$(Z.L(I,J) EQ 1),
        Z.LO(I,J)= 0;
        Z.UP(I,J)= 1.0;
    ]; {loop}

    ELSE PUT @5,'Infeasible budget level'/;
    ]; {if}

    LOST.HDLL= 0;
    PUTPAGE;

    ]; {if budgeta}
    *-----

    *Summary report of the Losers

    IF[BUDGETA2, {then}

        PUTHD '#',TESTNUM:<2:0,' Summary of Losers'/
        @5,'_____'////;

        PUTHD 'MDEP TITLE',@28,'MDEP/INC',@38,'TOT-ASPIRED',@51,'WAR-VALUE'/;
        PUTHD '_____',@28,'_____',@38,'_____',@51,'_____'//;

        LOOP[IJ(II,JJ)$(Z.L(II,JJ) EQ 0),
            PUT @1,I.TE(II),@28,II.TL:4,JJ.TL:<2:0,@38,TOTASPIRE(II,JJ):<10:0
            @51,WARVAL(II,JJ):<5:2//;
        ]; {loop}

```

```

LOST.HDLL=0;
PUTPAGE;

]; {if budgeta2}

*-----
SCALAR
    BUDGETWT;

BUDGETWT=0.4;

POSITIVE VARIABLES
    NBUDGET(T) Negative deviation from the annual budget level
    ;

FREE VARIABLE
    DEVIAT3 Sum of all the weighted goal deviations;

EQUATIONS
    OBJDEF3      Objective function
    COSTGOAL(T)  Budget goal;

COSTGOAL(T)..SUM((IJ),X(IJ,T)*ASPIRE(IJ,T))/BUDGET(T)=E=1-NBUDGET(T);
*VARPERSIS(IJ(I,J))..Z(I,J)=E= Z01(I,J)+ZPOS(I,J)-ZNEG(I,J);

OBJDEF3..
    SUM(t, WEIGHT1(t) * NWARVAL(t))
  + SUM((k,t), WEIGHT2(t) * NBAL1(k,t))
  + SUM((k,t), WEIGHT3(t) * NBAL2(k,t))
  + SUM((k,t), WEIGHT2(t) * PBAL1(k,t))
  + SUM((k,t), WEIGHT3(t) * PBAL2(k,t))
  + SUM((IJ,t) $ (ASPIRE(IJ,t) * ASPIRE(IJ,t-1)),
    WEIGHT4(t) * NTURB(IJ,t)) / SCALTURB
  + SUM(T,BUDGETWT*NBUDGET(T))
  =E= DEVIAT3 ;

MODEL MAXBUDGET/WARVALUE,BALANCE,TURBULENCE,COSTGOAL,SUSTAIN
LINKAGE,FRACFUND,INCREMENT,{YRMIN,}LOGCLE,LOGCEQ
OBJDEF3/;

*-----

IF[LOGICAL OR FEASIBL, {then}

*Summary of infeasible and feasible Losers

TESTNUM= TESTNUM +1;
PUTHD '#',TESTNUM:<2:0,' Summary of Losers'/
      @5,'_____'/;;

PUT /'Summary list of infeasible MDEPs'/
    '_____'/;
LOOP[ (II,JJ)$INFEASIBLE(II,JJ),
    PUT I.TE(II):27,II.TL:4,' ',JJ.TL:2/
]; {loop}

PUT/'Summary list of feasible MDEPs'/
    '_____'/;
LOOP[ (II,JJ)$FEASIBLE(II,JJ),
    PUT I.TE(II):27,II.TL:4,' ',JJ.TL:2/
]; {loop}

```

```
]; {loop}  
]; {if}  
PUTCLOSE LOST;
```


APPENDIX B. OPTION FILE

This appendix presents the option file that directs the scope of the sensitivity analysis.

*Option file for RDA3

* 1 = yes 0 = no

*-----

*RDA3 model options

PARAMETER FULL Indicate 100% funding OR partial funding of mandates;
 FULL= 1;

*-----

*Sensitivity analysis options

PARAMETERS

LOGICAL Perform infeasibility screening with submodel of logical constraints
CONFLICT Un-mandate mandated MDEPs that conflict in the logical constraints
ALLMAND Un-mandate all originally mandated MDEPs and solve
GROUPMAN Un-mandate groups of mandated MDEPs and solve
FEASIBL Force-in each feasible loser or all losers if LOGICAL not performed
* one at a time
GROUPFES Force-in a group of feasible MDEPs at one time and solve
BUDGETB Analyze effect of changes in annual budget levels BEFORE decision
BUDGETA Analyze effect of changes in annual budget levels AFTER decision
BUDGETA2 Analyze effect of changes in annual budget levels AFTER decision
;

LOGICAL= 1;
CONFLICT= 1;
ALLMAND= 1;
GROUPMAN= 0;
FEASIBL= 1;
GROUPFES= 0;
BUDGETB= 0;
BUDGETA= 0;
BUDGETA2= 0;

*-----

*Unmandate a group of mandated MDEPs

*Instruction: indicate desired group by assigning to set MANGRP as shown

* below

SET MANGRP(I,J) group of mandated MDEPs;

* MANGRP("FPJC","01")= YES; **EXAMPLE**
* MANGRP("FPSA","06")= YES; **EXAMPLE**
* add group below example *
 MANGRP("FPEL","05")= YES;
 MANGRP("FPSA","01")= YES;
 MANGRP("FPSA","06")= YES;
 MANGRP("FPSB","01")= YES;

```

*-----
*Force-in a group of feasible MDEPs

*Instruction: indicate desired group by assigning to set FEASGRP as shown
*
*      below

SET FEASGRP(I,J) group of feasible MDEPs;
*   FEASGRP("FPLF","06")= YES;    **EXAMPLE**
*   FEASGRP("FPLF","06")= YES;
*   FEASGRP("FPJB","06")= YES;
*   FEASGRP("FPMM","04")= YES;
*-----

*Change annual budget levels for analysis
*Budget in thousands of dollars

PARAMETER ALTBUDGET(T) An alternative budget allocation for analysis;

    ALTBUDGET("FY94")= 8000000;
    ALTBUDGET("FY95")= 8000000;
    ALTBUDGET("FY96")= 8000000;
    ALTBUDGET("FY97")= 8000000;
    ALTBUDGET("FY98")= 8000000;
    ALTBUDGET("FY99")= 8000000;
    ALTBUDGET("FY00")= 8000000;
    ALTBUDGET("FY01")= 8000000;
    ALTBUDGET("FY02")= 8000000;
    ALTBUDGET("FY03")= 8000000;
    ALTBUDGET("FY04")= 8000000;
    ALTBUDGET("FY05")= 8000000;
    ALTBUDGET("FY06")= 8000000;
    ALTBUDGET("FY07")= 8000000;
    ALTBUDGET("FY08")= 8000000;

*-----
*Original budget levels
$ONTEXT
    ALTBUDGET("FY94")= 10000000;
    ALTBUDGET("FY95")= 10000000;
    ALTBUDGET("FY96")= 10000000;
    ALTBUDGET("FY97")= 10000000;
    ALTBUDGET("FY98")= 10000000;
    ALTBUDGET("FY99")= 11000000;
    ALTBUDGET("FY00")= 11000000;
    ALTBUDGET("FY01")= 11000000;
    ALTBUDGET("FY02")= 11000000;
    ALTBUDGET("FY03")= 11000000;
    ALTBUDGET("FY04")= 12000000;
    ALTBUDGET("FY05")= 12000000;
    ALTBUDGET("FY06")= 12000000;
    ALTBUDGET("FY07")= 12000000;
    ALTBUDGET("FY08")= 12000000;
$OFFTEXT
*-----

```

APPENDIX C. LOGICAL CONSTRAINTS

This appendix presents the original formulation and the generic formulation of the logical constraints for comparison.

A. ORIGINAL FORMULATION OF THE LOGICAL CONSTRAINTS

* logical constraints

EQUATIONS

EXCLUSIV1	don't fund mutually exclusive MDEPs
EXCLUSIV2	don't fund mutually exclusive MDEPs
EXCLUSIV3	don't fund mutually exclusive MDEPs
EXCLUSIV4	don't fund mutually exclusive MDEPs
EXCLUSIV5	don't fund mutually exclusive MDEPs
SUB1	don't fund mutually exclusive MDEP subsets
SUB2	don't fund mutually exclusive MDEP subsets
SUB3	don't fund mutually exclusive MDEP subsets
SUB4	don't fund mutually exclusive MDEP subsets
SUB5	don't fund mutually exclusive MDEP subsets
COMP1	fund complementary MDEPs
COMP2	fund complementary MDEPs
COMP3	fund complementary MDEPs
COMP4	fund complementary MDEPs
COMP5	fund complementary MDEPs
COMP6	fund complementary MDEPs
COMP7	fund complementary MDEPs
COMP8	fund complementary MDEPs
COMP9	fund complementary MDEPs
COMP10	fund complementary MDEPs
COMP11	fund complementary MDEPs
COMP12	fund complementary MDEPs
COMP13	fund complementary MDEPs
COMP14	fund complementary MDEPs
COMP15	fund complementary MDEPs
COMP16	fund complementary MDEPs
COMP17	fund complementary MDEPs
COMP18	fund complementary MDEPs
COMP19	fund complementary MDEPs
;	

* formulation of logical constraints

* don't fund mutually exclusive MDEPs

EXCLUSIV1.. Z("FPHB","01") + Z("FPSG","01") =L= 1.0 ;

```

EXCLUSIV2..      Z("FPSF","01") + Z("RF08","01") =L= 1.0 ;

EXCLUSIV3..      Z("FPSB","01") + Z("FPSJ","01")
                  + Z("RA09","01") =L= 1.0 ;

EXCLUSIV4..      Z("FPSD","01") + Z("FPNB","01")
                  + Z("FPDC","01") =L= 1.0 ;

EXCLUSIV5..      Z("FPXX","01") + Z("FPLK","02")
                  + Z("FPSD","01") =L= 1.0 ;

*   don't fund mutually exclusive MDEP subsets

SUB1..           Z("FPEA","01") =E= Z("FPEL","02") ;
SUB2..           Z("FPEA","01") =E= Z("FPEL","05") ;
SUB3..           Z("FPEA","01") + Z("FPGA","01") =L= 1.0 ;

SUB4..           Z("FPSA","01") =E= Z("FPSA","06") ;
SUB5..           Z("FPSA","01") + Z("FPSE","01") =L= 1.0 ;

*   fund complementary MDEPs

COMP1..          Z("FPSG","01") =E= Z("FPSH","01") ;

COMP2..          Z("FPHB","01") =E= Z("FL6X","01") ;

COMP3..          Z("RA08","01") =E= Z("FPSE","01") ;
COMP4..          Z("RA08","01") =E= Z("RF01","01") ;
COMP5..          Z("RA08","01") =E= Z("RF08","01") ;

COMP6..          Z("FPLF","01") =E= Z("FPFL","01") ;
COMP7..          Z("FPLF","01") =E= Z("FPHC","01") ;
COMP8..          Z("FPLF","01") =E= Z("FPLG","01") ;
COMP9..          Z("FPLF","01") =E= Z("FPLX","01") ;
COMP10..         Z("FPLF","01") =E= Z("FPLC","01") ;
COMP11..         Z("FPLF","01") =E= Z("FPJA","01") ;

COMP12..         Z("FPEA","01") =E= Z("FPED","01") ;
COMP13..         Z("FPEA","01") =E= Z("FP EE","01") ;
COMP14..         Z("FPEA","01") =E= Z("FPLE","01") ;

COMP15..         Z("FPFP","01") =E= Z("FPWB","01") ;
COMP16..         Z("FPFP","01") =E= Z("FPFL","01") ;
COMP17..         Z("FPFP","01") =E= Z("FPFK","01") ;
COMP18..         Z("FPFP","01") =E= Z("FPFB","01") ;
COMP19..         Z("FPFP","01") =E= Z("FPWC","01") ;

```

B. GENERIC FORMULATION OF THE LOGICAL CONSTRAINTS

*Logical constraints

```

SETS
LLE logical constraints (less than or equal)
/EXC1*EXC5,SUB3,SUB5/

```



```

      LEQ logical constraints (equal to)
      /SUB1,SUB2,SUB4,COMP1*COMP19/;

SET INCON(I,J) increment inclusion switch;
      INCON(IJ(I,J))$(IJ(I,"01") AND ORD(J) GT 1)= YES;

SET INCON2(I,J) Copy of INCON switch;
      INCON2(IJ)$INCON(IJ) = YES;

SET LLEON(LLE) logc1e inclusion switch;
      LLEON(LLE)=YES;

SET LEQON(LEQ) logceq inclusion switch;
      LEQON(LEQ)=YES;

PARAMETER ALE(LLE,I,J) coefficients of less than logical constraints
      /EXC1.FPHB.01      1
      EXC1.FPSG.01      1
      EXC2.FPSF.01      1
      EXC2.RF08.01      1
      EXC3.FPSB.01      1
      EXC3.FPSJ.01      1
      EXC3.RA09.01      1
      EXC4.FPSD.01      1
      EXC4.FPNB.01      1
      EXC4.FPDC.01      1
      EXC5.FPXX.01      1
      EXC5.FPLK.02      1
      EXC5.FPSD.01      1
      SUB3.FPEA.01      1
      SUB3.FPGA.01      1
      SUB5.FPSA.01      1
      SUB5.FPSE.01      1
      /;

PARAMETER BLE(LLE) RHS of logical constraints (less than or equal)
      /EXC1*EXC5      1
      SUB3      1
      SUB5      1/;

PARAMETER AEQ(LEQ,I,J) coefficients of equal to logical constraints
      /SUB1.FPEA.01      1
      SUB1.FPEL.02      -1
      SUB2.FPEA.01      1
      SUB2.FPEL.05      -1
      SUB4.FPSA.01      1
      SUB4.FPSA.06      -1
      COMP1.FPSG.01      1
      COMP1.FPSH.01      -1
      COMP2.FPHB.01      1
      COMP2.FL6X.01      -1
      COMP3.RA08.01      1
      COMP3.FPSE.01      -1
      COMP4.RA08.01      1
      COMP4.RF01.01      -1
      COMP5.RA08.01      1
      COMP5.RF08.01      -1
      COMP6.FPLF.01      1
      COMP6.FPFL.01      -1
      COMP7.FPLF.01      1
      COMP7.FPHC.01      -1
      COMP8.FPLF.01      1

```

```

COMP8.FPLG.01    -1
COMP9.FPLF.01     1
COMP9.FPLX.01    -1
COMP10.FPLF.01    1
COMP10.FPLC.01   -1
COMP11.FPLF.01    1
COMP11.FPJA.01   -1
COMP12.FPEA.01    1
COMP12.FPED.01   -1
COMP13.FPEA.01    1
COMP13.FPEE.01   -1
COMP14.FPEA.01    1
COMP14.FPLE.01   -1
COMP15.FPFP.01    1
COMP15.FPWB.01   -1
COMP16.FPFP.01    1
COMP16.FPFL.01   -1
COMP17.FPFP.01    1
COMP17.FPFK.01   -1
COMP18.FPFP.01    1
COMP18.FPFB.01   -1
COMP19.FPFP.01    1
COMP19.FPWC.01   -1
    /;

PARAMETER BEQ(LEQ) RHS of logical constraints (equal to)
    /SUB1    0
    SUB2    0
    SUB4    0
    COMP1*COMP19    0/;

POSITIVE VARIABLES
    INFES(LLE) Elastic variable accounting for infeasibility in LLE
    PINFES(LEQ) Elastic variable accounting for positive infeasibility
    NINFES(LEQ) Elastic variable accounting for negative infeasibility
    INCINFES(I,J) Elastic variable accounting for infeasibility in INCREMENT;

EQUATIONS
    LOGCLE(LLE) logical constraints (less than or equal)
    LOGCEQ(LEQ) logical constraints (equal to)
    ;

LOGCLE(LLE)$ (LLEON(LLE)) ..
    SUM(IJ,ALE(LLE,IJ)*Z(IJ))-INFES(LLE)=L=BLE(LLE);

LOGCEQ(LEQ)$ (LEQON(LEQ)) ..
    SUM(IJ,AEQ(LEQ,IJ)*Z(IJ))-PINFES(LEQ)+NINFES(LEQ)=E=BEQ(LEQ);

INFES.FX(LLE)=0;
PINFES.FX(LEQ)=0;
NINFES.FX(LEQ)=0;
INCINFES.FX(I,J)=0;

```

APPENDIX D. BASELINE SOLUTION REPORTS

The results of the automatic sensitivity analysis for the baseline data are presented in this appendix.

A. BUDGET AND OSCOST ANALYSIS

#1 Budget and OSCOST Feasibility Analysis

Budget profile:

FY94	10000000
FY95	10000000
FY96	10000000
FY97	10000000
FY98	10000000
FY99	11000000
FY00	11000000
FY01	11000000
FY02	11000000
FY03	11000000
FY04	12000000
FY05	12000000
FY06	12000000
FY07	12000000
FY08	12000000

Maximum total OSCOST: 999999999

Result: All losers are budget and OSCOST feasible

B. SUMMARY OF LOSERS

This summary is the finale of the automatic analysis and is presented up front here for the reader's benefit.

#6 Summary of Losers

Summary list of infeasible MDEPs

FPGA	FPGA 01
FPGA	FPGA 02
FPSE	FPSE 01
FPSE	FPSE 02
FPSJ	FPSJ 01
RA08	RA08 01
RA08	RA08 06
RA09	RA09 01
RA09	RA09 02
RF01	RF01 01
RF08	RF08 01

Summary list of feasible MDEPs

FL6X	FL6X 01
FL6X	FL6X 02
FPHB	FPHB 01
FPJB	FPJB 06
FPLF	FPLF 06
FPLG	FPLG 02
FPLK	FPLK 02
FPLK	FPLK 04
FPMM	FPMM 04
FPNB	FPNB 01
FPNE	FPNE 05
FPSD	FPSD 01
FPSD	FPSD 04
FPSD	FPSD 06

C. LOGICAL INFEASIBILITY ANALYSIS

#2 Logical Constraint Infeasibility Analysis

1. Infeasible loser: FPGA

FPGA01

Filter pass #1

Constraints Violated:

Mandated: Must fund FPEL

FPEL05

SUB2 , Fund both or neither
FPEL

FPEA01
FPEL05

SUB3 , Fund either but not both
FPEA
FPGA

FPEA01
FPGA01

Irreducible inconsistent set (IIS):

Mandated: Must fund FPEL

FPEL05

Fund either but not both: FPEA
FPGA

FPEA01
FPGA01

Fund both or neither: FPEA

FPEA01

FPEL	FPEL05
2. Infeasible loser: FPGA	FPGA02
Filter pass #1	
Constraints Violated:	
Mandated: Must fund FPEL	FPEL05
SUB2 , Fund both or neither	FPEA01
FPGA	FPEL05
Must fund FPGA01 before FPGA	FPGA02
SUB3 , Fund either but not both	FPEA01
FPGA	FPGA01
Irreducible inconsistent set (IIS):	
Must fund FPGA01 before FPGA	FPGA02
Mandated: Must fund FPEL	FPEL05
Fund either but not both: FPEA	FPEA01
FPGA	FPGA01
Fund both or neither: FPEA	FPEA01
FPEL	FPEL05
3. Infeasible loser: FPSE	FPSE01
Filter pass #1	
Constraints Violated:	
SUB5 , Fund either but not both	FPSA01
FPSE	FPSE01
Mandated: Must fund FPSA	FPSA01
Mandated: Must fund FPSA	FPSA06
Irreducible inconsistent set (IIS):	
Mandated: Must fund FPSA	FPSA01
Fund either but not both: FPSA	FPSA01
FPSE	FPSE01
4. Infeasible loser: FPSE	FPSE02
Filter pass #1	
Constraints Violated:	
Must fund FPSE01 before FPSE	FPSE02
SUB5 , Fund either but not both	FPSA01
FPSE	FPSE01

Mandated: Must fund FPSA	FPSA01
Mandated: Must fund FPSA	FPSA06

Irreducible inconsistent set (IIS):

Must fund FPSE01 before FPSE	FPSE02
Mandated: Must fund FPSA	FPSA01
Fund either but not both: FPSA	FPSA01
FPSE	FPSE01

5. Infeasible loser: FPSJ FPSJ01

Filter pass #1

Constraints Violated:

Mandated: Must fund FPSB	FPSB01
EXC3 , Fund either but not bothFPSB	FPSB01
FPSJ	FPSJ01
RA09	RA0901

Irreducible inconsistent set (IIS):

Mandated: Must fund FPSB	FPSB01
Fund either but not both: FPSB	FPSB01
FPSJ	FPSJ01
RA09	RA0901

6. Infeasible loser: RA08 RA0801

Filter pass #1

Constraints Violated:

COMP3 , Fund both or neitherFPSB	FPSE01
RA08	RA0801
SUB5 , Fund either but not bothFPSA	FPSA01
FPSE	FPSE01
Mandated: Must fund FPSA	FPSA01
Mandated: Must fund FPSA	FPSA06

Irreducible inconsistent set (IIS):

Mandated: Must fund FPSA	FPSA01
Fund either but not both: FPSA	FPSA01
FPSE	FPSE01
Fund both or neither: FPSB	FPSE01
RA08	RA0801

7. Infeasible loser: RA08

RA0806

Filter pass #1

Constraints Violated:

Must fund RA0801 before RA08

RA0806

COMP3 , Fund both or neither
RA08

FPSE01
RA0801

SUB5 , Fund either but not both
FPSE

FPSA01
FPSE01

Mandated: Must fund FPSA
Mandated: Must fund FPSA

FPSA01
FPSA06

Irreducible inconsistent set (IIS):

Must fund RA0801 before RA08

RA0806

Mandated: Must fund FPSA

FPSA01

Fund either but not both: FPSA
FPSE

FPSA01
FPSE01

Fund both or neither: FPSE
RA08

FPSE01
RA0801

8. Infeasible loser: RA09

RA0901

Filter pass #1

Constraints Violated:

Mandated: Must fund FPSB

FPSB01

EXC3 , Fund either but not both
FPSJ
RA09

FPSB01
FPSJ01
RA0901

Irreducible inconsistent set (IIS):

Mandated: Must fund FPSB

FPSB01

Fund either but not both: FPSB
FPSJ
RA09

FPSB01
FPSJ01
RA0901

9. Infeasible loser: RA09

RA0902

Filter pass #1

Constraints Violated:

Mandated: Must fund FPSB

FPSB01

Must fund RA0901 before RA09

RA0902

EXC3 , Fund either but not both
FPSJ
RA09

FPSB01
FPSJ01
RA0901

Irreducible inconsistent set (IIS):

Must fund RA0901 before RA09

RA0902

Mandated: Must fund FPSB

FPSB01

Fund either but not both: FPSB
FPSJ
RA09

FPSB01
FPSJ01
RA0901

10. Infeasible loser: RF01

RF0101

Filter pass #1

Constraints Violated:

COMP4 , Fund both or neither
RA08
RF01

RA0801
RF0101

COMP3 , Fund both or neither
FPSE
RA08

FPSE01
RA0801

SUB5 , Fund either but not both
FPSA
FPSE

FPSA01
FPSE01

Mandated: Must fund FPSA
Mandated: Must fund FPSA

FPSA01
FPSA06

Irreducible inconsistent set (IIS):

Mandated: Must fund FPSA

FPSA01

Fund either but not both: FPSA
FPSE

FPSA01
FPSE01

Fund both or neither: FPSE
RA08

FPSE01
RA0801

Fund both or neither: RA08
RF01

RA0801
RF0101

11. Infeasible loser: RF08

RF0801

Filter pass #1

Constraints Violated:

COMP5 , Fund both or neither	RA08	RA0801
	RF08	RF0801
COMP3 , Fund both or neither	FPSE	FPSE01
	RA08	RA0801
SUB5 , Fund either but not both	FPSE	FPSE01
		FPSE01
Mandated: Must fund FPSA		FPSA01
Mandated: Must fund FPSA		FPSA06

Irreducible inconsistent set (IIS):

Mandated: Must fund FPSA	FPSA01
Fund either but not both: FPSA	FPSA01
	FPSE01
	FPSE
Fund both or neither: FPSE	FPSE01
	RA0801
Fund both or neither: RA08	RA0801
	RF0801
	RF08

D. MANDATED PROJECT ANALYSIS

1. Conflicting Mandates

Mandated Projects	# Projects Forced-out	# Projects Enter	% Funding Before	% Funding After	Objective Function
FPEL,05	16	5	100	0	889.88
FPSA,01	0	0	100	100	919.63
FPSA,06	0	0	100	80	916.65
FPSB,01	0	0	100	100	919.63

Table 1. Summary of Conflicts Analysis

#3 Analysis of Mandated MDEPs that Conflict with Losers

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

1.Un-mandate: MDEP NWARVAL NBAL1 NBAL2 PBAL1 PBAL2 NTURB DEVIATION

FPEL	FPEL05	1327.13	2.20	0.43	2.09	0.52	15.02	889.88
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War-value

Forced out:	FPDB	FPDB 06	0.09
	FPDQ	FPDQ 02	0.21
	FPEA	FPEA 01	3.03
	FPEA	FPEA 02	0.45
	FPED	FPED 01	3.80
	FPED	FPED 04	0.30
	FPEE	FPEE 01	5.16
	FPEE	FPEE 02	0.45
	FPEL	FPEL 02	1.83
	FPEL	FPEL 05	0.45
	FPJC	FPJC 06	0.13
	FPLE	FPLE 01	19.74
	FPMK	FPMK 06	0.20
	FPSB	FPSB 04	0.20
	FPSG	FPSG 01	11.01
	FPSH	FPSH 01	11.01

War-value

Enter:	FL6X	FL6X 01	3.52
	FL6X	FL6X 02	0.44
	FPGA	FPGA 01	48.50
	FPGA	FPGA 02	45.45
	FPHB	FPHB 01	3.52

2.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSA	FPSA01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate:	FPSA	FPSA01
	Before: 746814	100.00%
	After: 746814	100.00%

3.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSA	FPSA06	1372.71	2.30	0.27	1.91	0.09	3.73	916.65

Funding change for mandate:	FPSA	FPSA06
	Before: 6052849	100.00%
	After: 4842279	80.00%

4.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSB	FPSB01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate:	FPSB	FPSB01
	Before: 365506	100.00%
	After: 365506	100.00%

2. All Mandates

#4 Analysis of All Mandated MDEPs

		NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3	RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

1.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPEG	FPEG01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate:	FPEG	FPEG01
	Before: 1458705	100.00%
	After: 1458705	100.00%

2.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPFL	FPFL05	1327.09	2.14	0.49	2.13	0.49	14.60	889.85

War-value

Forced out:	FPDQ	FPDQ 02	0.21
	FPEA	FPEA 01	3.03
	FPEA	FPEA 02	0.45
	FPED	FPED 01	3.80
	FPED	FPED 04	0.30
	FPPE	FPPE 01	5.16
	FPPE	FPPE 02	0.45
	FPPEL	FPPEL 02	1.83
	FPPEL	FPPEL 05	0.45
	FPJC	FPJC 06	0.13
	FPLE	FPLE 01	19.74
	FPMK	FPMK 06	0.20
	FPSB	FPSB 04	0.20
	FPSG	FPSG 01	11.01
	FPSH	FPSH 01	11.01

War-value

Enter:	FL6X	FL6X 01	3.52
	FL6X	FL6X 02	0.44
	FPGA	FPGA 01	48.50
	FPGA	FPGA 02	45.45
	FPHB	FPHB 01	3.52

3.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPFL	FPFL01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate:	FPFL	FPFL01
	Before: 705731	100.00%
	After: 705731	100.00%

4.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPJC	FPJC01	1372.57	2.27	0.24	1.80	0.15	5.37	916.56

Funding change for mandate: FPJC FPJC01
Before: 8278850 100.00%
After: 5737874 69.31%

5.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPMK	FPMK01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate: FPMK FPMK01
Before: 666772 100.00%
After: 666772 100.00%

6.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPMK	FPMK01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate: FPMM FPMM01
Before: 2048522 100.00%
After: 2048522 100.00%

7.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPNC	FPNC01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate: FPNC FPNC01
Before: 527576 100.00%
After: 527576 100.00%

8.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSA	FPSA01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

		NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS		1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate: FPSA FPSA01
Before: 746814 100.00%
After: 746814 100.00%

9.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSA	FPSA06	1372.71	2.30	0.27	1.91	0.09	3.73	916.65

Funding change for mandate: FPSA FPSA06
Before: 6052849 100.00%
After: 4842279 80.00%

10.Un-mandate:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSB	FPSB01	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Funding change for mandate:	FPWB	FPWB01
	Before: 1929687	100.00%
	After: 1929687	100.00%

Forced in Projects	# Projects Forced-out	# Projects Followed in	Objective Function
FL6X,01	2	3	921.67
FL6X,02	2	3	921.67
FPHB,01	2	3	921.67
FPJB,06	0	0	920.50
FPLF,06	0	0	920.88
FPLG,02	0	0	919.74
FPLK,02	2	0	919.96
FPLK,04	0	0	921.06
FPM,04	0	0	921.38
FPNB,01	2	0	960.72
FPNE,05	0	0	920.30
FPSD,01	5	1	1110.85
FPSD,04	5	2	1111.27
FPSD,06	5	1	1110.85

		NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3	RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

1.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FL6X	FL6X01	1382.17	2.46	0.34	1.74	0.08	10.11	921.67

War-value

Forced out:	FPSG	FPSG 01	11.01
	FPSH	FPSH 01	11.01

War-value

Followed-in:	FL6X	FL6X 02	0.44
	FPHB	FPHB 01	3.52
	FPLG	FPLG 02	0.15

2.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FL6X	FL6X02	1382.17	2.46	0.34	1.74	0.08	10.11	921.67

War-value

Forced out:	FPSG	FPSG 01	11.01
	FPSH	FPSH 01	11.01

War-value

Followed-in:	FL6X	FL6X 01	3.52
	FPHB	FPHB 01	3.52
	FPLG	FPLG 02	0.15

3.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPHB	FPHB01	1382.17	2.46	0.34	1.74	0.08	10.11	921.67

War-value

Forced out:	FPSG	FPSG 01	11.01
	FPSH	FPSH 01	11.01

War-value

Followed-in:	FL6X	FL6X 01	3.52
	FL6X	FL6X 02	0.44
	FPLG	FPLG 02	0.15

4.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
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FPJB	FPJB061378.44	2.28	0.26	1.87	0.11	12.89	920.50
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5.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPLF	FPLF061379.00	2.30	0.27	1.85	0.16	11.84	920.88	

6.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPLG	FPLG021377.29	2.31	0.26	1.83	0.18	11.65	919.74	

7.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPLK	FPLK021377.61	2.30	0.29	1.85	0.09	11.54	919.96	

						War-value	
Forced out:	FPXX			FPXX 01		0.80	
	FPXX			FPXX 06		0.20	

8.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPLK	FPLK041379.27	2.28	0.25	1.89	0.09	11.04	921.06	

9.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPMO	FPMO041379.75	2.27	0.27	1.89	0.09	12.90	921.38	

10.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPNB	FPNB011436.45	2.22	0.26	1.83	0.08	12.72	960.72	

						War-value	
Forced out:	FPDC			FPDC 01		23.83	
	FPDC			FPDC 06		0.52	

11.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPNE	FPNE051378.14	2.27	0.26	1.87	0.10	11.97	920.30	

12.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSD	FPSD011660.63	2.22	0.16	1.81	0.16	8.45	1110.85	

						War-value	
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Forced out:	FPDC	FPDC 01	23.83
	FPDC	FPDC 06	0.52
	FPDQ	FPDQ 02	0.21
	FPXX	FPXX 01	0.80
	FPXX	FPXX 06	0.20

War-value

Followed-in:	FPSD	FPSD 06	0.29
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13.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSD	FPD041661.25	2.21	0.18	1.78	0.21	7.91	1111.27	

War-value

Forced out:	FPDC	FPDC 01	23.83
	FPDC	FPDC 06	0.52
	FPDQ	FPDQ 02	0.21
	FPXX	FPXX 01	0.80
	FPXX	FPXX 06	0.20

War-value

Followed-in:	FPSD	FPSD 01	6.86
	FPSD	FPSD 06	0.29

14.Force-in:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
FPSD	FPD061660.63	2.22	0.16	1.81	0.16	8.45	1110.85	

War-value

Forced out:	FPDC	FPDC 01	23.83
	FPDC	FPDC 06	0.52
	FPDQ	FPDQ 02	0.21
	FPXX	FPXX 01	0.80
	FPXX	FPXX 06	0.20

War-value

Followed-in:	FPSD	FPSD 01	6.86
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APPENDIX E. BUDGET AND OSCOST INFEASIBILITY

This appendix contains the complete results from the budget and operating and support cost tests.

A. BUDGET INFEASIBILITY

Case	Minimum Fraction of Total Aspired to be Funded	Minimum Annual Funding Level	Funding Policy for Mandates	# Projects Not Funded Because They Violate the Budget Constraint
1	.6 for "01" increments .8 for all others	0	Full	15
2	.6 for "01" increments .8 for all others	0	Partial	2
3	0	.75	Full	25
4	0	.75	Partial	3

Table 1. Budget Infeasibility Results

1. Case 1

#1 Budget and OSCOST Feasibility Analysis

Budget profile:

FY94	4000000
FY95	4000000
FY96	4000000
FY97	4000000
FY98	4000000
FY99	3000000
FY00	3000000
FY01	3000000
FY02	3000000
FY03	3000000
FY04	5000000
FY05	5000000
FY06	5000000
FY07	5000000
FY08	5000000

Maximum total OSCOST: 999999999

Result: 1. FPGA FPGA01
Violates the total budget constraint

- ## 2. Case 2

```
Budget profile:      FY94 4000000
                     FY95 4000000
                     FY96 4000000
                     FY97 4000000
                     FY98 4000000
                     FY99 3000000
                     FY00 3000000
                     FY01 3000000
                     FY02 3000000
                     FY03 3000000
                     FY04 5000000
```

FY05 5000000
FY06 5000000
FY07 5000000
FY08 5000000

Maximum total OSCOST: 999999999

Result: 1. FPGA FPGA01
Violates the total budget constraint
2. FPSE FPSE02
Violates the total budget constraint

3. Case 3

#1 Budget and OSCOST Feasibility Analysis

Budget profile: FY94 2000000
FY95 10000000
FY96 10000000
FY97 10000000
FY98 2000000
FY99 11000000
FY00 11000000
FY01 11000000
FY02 2000000
FY03 11000000
FY04 12000000
FY05 12000000
FY06 2000000
FY07 12000000
FY08 12000000

Maximum total OSCOST: 999999999

Result: 1. FL6X FL6X01
Violates the budget constraint in year: FY94
FY98
2. FL6X FL6X02
Violates the budget constraint in year: FY94
FY98
3. FPGA FPGA01
Violates the budget constraint in year: FY94
FY98
FY02
FY06
4. FPGA FPGA02
Violates the budget constraint in year: FY94
FY98
5. FPHB FPHB01
Violates the budget constraint in year: FY94

		FY98
6.	FPJB	FPJB06
	Violates the budget constraint in year:	FY94 FY98
7.	FPLF	FPLF06
	Violates the budget constraint in year:	FY94 FY98
8.	FPLG	FPLG02
	Violates the budget constraint in year:	FY94 FY98
9.	FPLK	FPLK02
	Violates the budget constraint in year:	FY94 FY98
10.	FPLK	FPLK04
	Violates the budget constraint in year:	FY94 FY98
11.	FPMM	FPMM04
	Violates the budget constraint in year:	FY94 FY98
12.	FPNB	FPNB01
	Violates the budget constraint in year:	FY94 FY98
13.	FPNE	FPNE05
	Violates the budget constraint in year:	FY94 FY98
14.	FPSD	FPSD01
	Violates the budget constraint in year:	FY94 FY98
15.	FPSD	FPSD04
	Violates the budget constraint in year:	FY94 FY98
16.	FPSD	FPSD06
	Violates the budget constraint in year:	FY94 FY98
17.	FPSE	FPSE01
	Violates the budget constraint in year:	FY94 FY98

18. FPSE	FPSE02	
Violates the budget constraint in year:		FY94
		FY98
		FY02
		FY06
19. FPSJ	FPSJ01	
Violates the budget constraint in year:		FY94
		FY98
		FY06
20. RA08	RA0801	
Violates the budget constraint in year:		FY94
		FY98
21. RA08	RA0806	
Violates the budget constraint in year:		FY94
		FY98
22. RA09	RA0901	
Violates the budget constraint in year:		FY94
		FY98
23. RA09	RA0902	
Violates the budget constraint in year:		FY94
		FY98
24. RF01	RF0101	
Violates the budget constraint in year:		FY94
		FY98
25. RF08	RF0801	
Violates the budget constraint in year:		FY94
		FY98

4. Case 4

#1 Budget and OSCOST Feasibility Analysis

Budget profile:	FY94 2000000
	FY95 10000000
	FY96 10000000
	FY97 10000000
	FY98 2000000
	FY99 11000000
	FY00 11000000
	FY01 11000000
	FY02 2000000
	FY03 11000000

FY04 12000000
FY05 12000000
FY06 2000000
FY07 12000000
FY08 12000000

Maximum total OSCOST: 999999999

Result: 1. FPGA FPGA01
Violates the budget constraint in year: FY94
FY98
FY02
FY06

2. FPSE FPSE02
Violates the budget constraint in year: FY98
FY06

3. FPSJ FPSJ01
Violates the budget constraint in year: FY06

B. OSCOST INFEASIBILITY

Case	Maximum Allowable Operating and Support Cost	Funding Policy for Mandates	# Projects Not Funded Because They Violate the Maximum Operating and Support Costs
1	\$50 Billion	Full	13
2	\$50 Billion	Partial	1

Table 2. OSCOST infeasibility results for the baseline data with the maximum allowable operating and support cost reduced to cause infeasibility. The effect of the funding policy for mandated projects is evident. There is a substantial reduction in the number of projects that are not funded because they violate the maximum allowable operating and support costs.

1. Case 1

#1 Budget and OSCOST Feasibility Analysis

Budget profile: FY94 10000000
FY95 10000000
FY96 10000000
FY97 10000000
FY98 10000000
FY99 11000000

Maximum total OSCOST: 500000000

2. Case 2

```
Budget profile:  FY94 10000000
                  FY95 10000000
```

FY96 10000000
FY97 10000000
FY98 10000000
FY99 11000000
FY00 11000000
FY01 11000000
FY02 11000000
FY03 11000000
FY04 12000000
FY05 12000000
FY06 12000000
FY07 12000000
FY08 12000000

Maximum total OSCOST: 50000000

Result: 1. RA08 RA0801
Does not adhere to the maximum operation and support costs.

APPENDIX F. ANALYSIS OF MULTIPLE LOSERS AND MANDATES

This appendix shows the results obtained after un-mandating a group of mandated projects, as well as the results from forcing in a group of feasible losers.

A. BUDGET PROFILE

#1 Budget and OSCOST Feasibility Analysis

Budget profile:

FY94	10000000
FY95	10000000
FY96	10000000
FY97	10000000
FY98	10000000
FY99	11000000
FY00	11000000
FY01	11000000
FY02	11000000
FY03	11000000
FY04	12000000
FY05	12000000
FY06	12000000
FY07	12000000
FY08	12000000

Maximum total OSCOST: 999999999

Result: All losers are budget and OSCOST feasible

B. UN-MANDATING A GROUP OF MANDATED PROJECTS

#2 Analysis of a Specified Group of Mandated MDEPs

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Group Un-Mandated Result:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
		1192.24	2.43	0.35	2.22	0.56	13.77	799.03

		War-value
1. FPEL	FPEL05	0.45
2. FPSA	FPSA01	9.69

3. FPSA	FPSA06	0.80
4. FPSB	FPSB01	9.69

War-value

Forced out:	FPDB	FPDB 06	0.09
	FPDQ	FPDQ 02	0.21
	FPEA	FPEA 01	3.03
	FPEA	FPEA 02	0.45
	FPED	FPED 01	3.80
	FPED	FPED 04	0.30
	FPEE	FPEE 01	5.16
	FPEE	FPEE 02	0.45
	FPPEL	FPPEL 02	1.83
	FPPEL	FPPEL 05	0.45
	FPJC	FPJC 02	0.32
	FPJC	FPJC 06	0.13
	FPLE	FPLE 01	19.74
	FPSA	FPSA 01	9.69
	FPSA	FPSA 06	0.80
	FPSB	FPSB 04	0.20
	FPSF	FPSF 01	8.06
	FPSG	FPSG 01	11.01
	FPSH	FPSH 01	11.01

War-value

Enter:	FL6X	FL6X 01	3.52
	FL6X	FL6X 02	0.44
	FPGA	FPGA 01	48.50
	FPGA	FPGA 02	45.45
	FPHB	FPHB 01	3.52
	FPSE	FPSE 01	15.64
	FPSE	FPSE 02	4.44
	RA08	RA08 01	3.23
	RF01	RF01 01	1.61
	RF08	RF08 01	1.67

Funding change for mandate:	FPSB	FPSB01
	Before: 365506	100.00%
	After: 365506	100.00%

#2 Summary of Losers

MDEP TITLE	MDEP/INC	TOT-ASPIRED	WAR-VALUE
FPDB	FPDB06	1836800	0.09
FPDQ	FPDQ02	650800	0.21
FPEA	FPEA01	609387	3.03
FPEA	FPEA02	129000	0.45
FPED	FPED01	375000	3.80
FPED	FPED04	487089	0.30
FPEE	FPEE01	194949	5.16
FPEE	FPEE02	299435	0.45
FPPEL	FPPEL02	5313792	1.83
FPPEL	FPPEL05	1728400	0.45
FPJB	FPJB06	582917	0.13
FPJC	FPJC02	3232000	0.32

FPJC	FPJC06	548523	0.13
FPLE	FPLE01	179761	19.74
FPLF	FPLF06	1778500	0.15
FPLG	FPLG02	1896100	0.15
FPLK	FPLK02	1253500	0.80
FPLK	FPLK04	1341264	0.20
FPMM	FPMM04	1332600	0.20
FPNB	FPNB01	1300461	25.80
FPNE	FPNE05	692100	0.12
FPSA	FPSA01	746814	9.69
FPSA	FPSA06	6052849	0.80
FPSB	FPSB04	1052000	0.20
FPSD	FPSD01	4385149	6.86
FPSD	FPSD04	1381651	0.29
FPSD	FPSD06	3496890	0.29
FPSF	FPSF01	2923196	8.06
FPSG	FPSG01	6015816	11.01
FPSH	FPSH01	2642575	11.01
FPSJ	FPSJ01	12909581	1.62
RA08	RA0806	1086904	0.16
RA09	RA0901	127800	3.23
RA09	RA0902	11347	0.20

C. FORCING IN A GROUP OF FEASIBLE LOSERS

#3 Analysis of a Specified Group of Feasible Losers

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Group Force-in Result:	MDEP	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
	1384.08	2.29	0.29	1.85	0.17	14.36	924.28	

		War-value
1. FPJB	FPJB06	0.13
2. FPLF	FPLF06	0.15
3. FPMM	FPMM04	0.20

		War-value
Forced out: FPDQ	FPDQ 02	0.21

#3 Summary of Losers

MDEP TITLE	MDEP/INC	TOT-ASPIRED	WAR-VALUE
FL6X	FL6X01	98700	3.52
FL6X	FL6X02	111500	0.44
FPDQ	FPDQ02	650800	0.21
FPGA	FPGA01	35381174	48.50
FPGA	FPGA02	1905700	45.45
FPHB	FPHB01	620551	3.52
FPLG	FPLG02	1896100	0.15

FPLK	FPLK02	1253500	0.80
FPLK	FPLK04	1341264	0.20
FPNB	FPNB01	1300461	25.80
FPNE	FPNE05	692100	0.12
FPSD	FPSD01	4385149	6.86
FPSD	FPSD04	1381651	0.29
FPSD	FPSD06	3496890	0.29
FPSE	FPSE01	717622	15.64
FPSE	FPSE02	17100303	4.44
FPSJ	FPSJ01	12909581	1.62
RA08	RA0801	256148	3.23
RA08	RA0806	1086904	0.16
RA09	RA0901	127800	3.23
RA09	RA0902	11347	0.20
RF01	RF0101	240053	1.61
RF08	RF0801	608248	1.67

APPENDIX G. SENSITIVITY ANALYSIS ON THE BUDGET

The results for the three models investigated to conduct sensitivity analysis on the budget allocation are shown here. They are: Model 1- RDA³ unchanged, Model 2- RDA³ with the originally funded projects fixed into the solution, Model 3- RDA³ with variable persistence applied.

A. FEASIBLE BUDGET PROFILE

Budget profile:

FY94	8000000
FY95	8000000
FY96	8000000
FY97	8000000
FY98	8000000
FY99	9000000
FY00	9000000
FY01	9000000
FY02	9000000
FY03	9000000
FY04	10000000
FY05	10000000
FY06	10000000
FY07	10000000
FY08	10000000

1. Using the original RDA³ model

#1 Budget Analysis Before Decision

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
New results:	1563.23	2.14	0.25	1.94	0.44	6.94	1044.55

Budget profile:

FY94	8000000
FY95	8000000
FY96	8000000
FY97	8000000
FY98	8000000
FY99	9000000
FY00	9000000

FY01 9000000
 FY02 9000000
 FY03 9000000
 FY04 10000000
 FY05 10000000
 FY06 10000000
 FY07 10000000
 FY08 10000000

		War-value
Forced out:		
FPDM	FPDM 01	0.13
FPDQ	FPDQ 02	0.21
FPEQ	FPEQ 01	0.30
FPJB	FPJB 02	0.37
FPJC	FPJC 06	0.13
FPMC	FPMC 05	0.28
FPMH	FPMH 02	0.58
FPMH	FPMH 03	0.20
FPMK	FPMK 04	0.28
FPMK	FPMK 06	0.20
FPNA	FPNA 01	1.36
FPNE	FPNE 02	0.49
FPSB	FPSB 04	0.20
FPWC	FPWC 05	0.11
FPXK	FPXK 02	0.68
RA31	RA31 01	0.29
RA31	RA31 06	0.20
RE02	RE02 01	0.37
RF02	RF02 02	0.11
RF03	RF03 06	0.11
RF09	RF09 06	0.16
<hr/>		
TOTALS: old-->	% of Budget: 95.89	2.6068E+8 1.5823E+8 60.70
new-->	% of Budget: 99.88	2.6068E+8 1.3484E+8 51.73

2. Fixing the Previous Solution

#3 Budget Analysis After Decision (old solution fixed)

#4 Budget and OSCOST Feasibility Analysis (for budget analysis)

Budget profile:

FY94 8000000
 FY95 8000000
 FY96 8000000
 FY97 8000000
 FY98 8000000
 FY99 9000000
 FY00 9000000
 FY01 9000000
 FY02 9000000
 FY03 9000000

FY04 10000000
 FY05 10000000
 FY06 10000000
 FY07 10000000
 FY08 10000000

Maximum total OSCOST: 999999999

Result: The original solution is budget and OSCOST feasible

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
New results:	1673.16	2.34	0.36	2.25	0.45	19.92	1118.02

TOTALS: old-->	% of Budget: 95.89	2.6068E+8	1.5823E+8	60.70
new-->	% of Budget: 100.00	2.6068E+8	1.3500E+8	51.79

3. Applying Variable Persistence

#2 Budget Analysis After Decision (with persistence)

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
New results:	1673.16	2.34	0.36	2.25	0.45	19.92	1118.02

Budget profile:

FY94 8000000
 FY95 8000000
 FY96 8000000
 FY97 8000000
 FY98 8000000
 FY99 9000000
 FY00 9000000
 FY01 9000000
 FY02 9000000
 FY03 9000000
 FY04 10000000
 FY05 10000000
 FY06 10000000
 FY07 10000000
 FY08 10000000

TOTALS: old-->	% of Budget: 95.89	2.6068E+8	1.5823E+8	60.70
new-->	% of Budget: 100.00	2.6068E+8	1.3500E+8	51.79

B. INFEASIBLE BUDGET PROFILE

Budget profile:

FY94	8000000
FY95	8000000
FY96	8000000
FY97	8000000
FY98	8000000
FY99	8000000
FY00	8000000
FY01	8000000
FY02	8000000
FY03	8000000
FY04	8000000
FY05	8000000
FY06	8000000
FY07	8000000
FY08	8000000

1. Using the Original RDA³ Model

#1 Budget Analysis Before Decision

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
New results:	1588.86	2.15	0.70	2.03	0.50	3.93	1060.41

Budget profile:

FY94	8000000
FY95	8000000
FY96	8000000
FY97	8000000
FY98	8000000
FY99	8000000
FY00	8000000
FY01	8000000
FY02	8000000
FY03	8000000
FY04	8000000
FY05	8000000
FY06	8000000
FY07	8000000
FY08	8000000

		War-value
Forced out:	FPDE	0.48
	FPDM	0.13

FPDQ	FPDQ 02	0.21
FPEQ	FPEQ 01	0.30
FPJB	FPJB 02	0.37
FPJC	FPJC 06	0.13
FPMC	FPMC 05	0.28
FPMH	FPMH 02	0.58
FPMH	FPMH 03	0.20
FPMK	FPMK 04	0.28
FPMK	FPMK 06	0.20
FPNA	FPNA 01	1.36
FPNE	FPNE 02	0.49
FPNG	FPNG 01	0.17
FPSB	FPSB 04	0.20
FPSG	FPSG 01	11.01
FPSH	FPSH 01	11.01
FPSL	FPSL 01	0.20
FPWC	FPWC 05	0.11
FPXK	FPXK 02	0.68
RA31	RA31 01	0.29
RA31	RA31 06	0.20
RE02	RE02 01	0.37
RF02	RF02 02	0.11
RF03	RF03 06	0.11
RF09	RF09 06	0.16
RJS2	RJS2 05	0.41

		War-value
Enter: FL6X	FL6X 01	3.52
FL6X	FL6X 02	0.44
FPHB	FPHB 01	3.52

TOTALS: old-->	% of Budget: 95.89	2.6068E+8	1.5823E+8	60.70
new-->	% of Budget: 97.84	2.6068E+8	1.1740E+8	45.04

2. Fixing the Previous Solution

#3 Budget Analysis After Decision (old solution fixed)

#4 Budget and OSCOST Feasibility Analysis (for budget analysis)

Budget profile:

FY94	8000000
FY95	8000000
FY96	8000000
FY97	8000000
FY98	8000000
FY99	8000000
FY00	8000000
FY01	8000000
FY02	8000000
FY03	8000000
FY04	8000000
FY05	8000000
FY06	8000000

FY07 8000000
FY08 8000000

Maximum total OSCOST: 999999999

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

Infeasible budget level

3. Applying Variable Persistence

#2 Budget Analysis After Decision (with persistence)

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
RDA3 RESULTS	1377.14	2.27	0.26	1.88	0.09	11.65	919.63

	NWARVAL	NBAL1	NBAL2	PBAL1	PBAL2	NTURB	DEVIATION
New results:	2030.58	2.31	0.54	2.34	0.50	79.16	1354.31

Budget profile:

FY94 8000000
FY95 8000000
FY96 8000000
FY97 8000000
FY98 8000000
FY99 8000000
FY00 8000000
FY01 8000000
FY02 8000000
FY03 8000000
FY04 8000000
FY05 8000000
FY06 8000000
FY07 8000000
FY08 8000000

		War-value
Forced out: FPSL	FPSL 01	0.20

TOTALS: old-->	% of Budget: 95.89	2.6068E+8	1.5823E+8	60.70
new-->	% of Budget: 100.00	2.6068E+8	1.2000E+8	46.03

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